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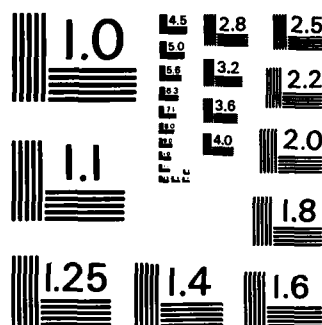
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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

A MATCHED FILTER ALGORITHM FOR
ACOUSTIC SIGNAL DETECTION

by

Dorsett Weston Jordan

June 1985

Thesis Advisor: R. Panholzer

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This thesis is a presentation of several alternative acoustic filter designs which allow Space Shuttle payload experiment initiation prior to launch. This initiation is accomplished independently of any spacecraft services by means of a matched band-pass filter tuned to the acoustic signal characteristic of the Auxiliary Power Unit (APU) which is brought up to operating RPMs approximately five minutes prior to launch.

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A Matched Filter Algorithm
for Acoustic Signal Detection

by

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B.S., University of Colorado, 1977

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ABSTRACT

This thesis is a presentation of several alternative acoustic filter designs which allow Space Shuttle payload experiment initiation prior to launch. This initiation is accomplished independently of any spacecraft services by means of a matched band-pass filter tuned to the acoustic signal characteristic of the Auxiliary Power Unit (APU) which is brought up to operating RPM's approximately five minutes prior to launch.

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I. INTRODUCTION

A. BACKGROUND

In April of 1981 a new era of space exploration was opened for mankind when the Space Shuttle successfully returned to Earth after its first orbital mission. Notwithstanding the significant capabilities which this new and radically different concept in space transportation has afforded traditionally large and well funded government and industrial agencies, the Space Shuttle has also ushered in the age of the small experimenter with limited access to funds who has an idea which needs to be tested in space and who now has a means of seeing that test realized.

The Get Away Special (GAS) Program was developed by the National Aeronautics and Space Administration (NASA) to afford qualifying teams of experimenters the opportunity to launch and orbit GAS payloads on a not-to-interfere space available basis during regularly scheduled Shuttle missions.

The main purpose for Shuttle missions is the conveyance into space and deployment of large, sophisticated instruments into Earth orbit. Because many primary mission payloads do not occupy the entirety of the Shuttle payload bay there is frequently opportunity for the additional

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deployment of GAS payloads during Shuttle missions [Ref. 1: pp. 8-9].

One significant requirement demanded of GAS experimenters is that each payload be self-contained within its standard size (5.0 cubic foot) NASA provided canister. Thus it is expected that each GAS experiment include provisions within its own confines for all electrical power, heating elements, data control and storage, and so on. In short, GAS payloads may not draw upon any Shuttle services for their normal operation beyond an on-off switch control which may be thrown locally by an astronaut should the Shuttle timeline of events allow for such intervention.

This requirement for a completely self-contained experiment necessitates a well-planned execution of tasks performed under automated control. Although the concession for astronaut involvement in experiment initiation is provided, during some critical periods it is not feasible for astronauts to tend to GAS payload requirements, e. g., during launch and landing phases. At these times it then becomes necessary to design for complete automation of GAS experimental control, to provide most significantly for independent initiation of experimentation.

B. STATEMENT OF GOAL

It is the purpose of this thesis to consider a design algorithm to accomplish an automated initiation of GAS

experimentation based solely upon the passive detection of a
well-defined event in the evolution of the Shuttle timeline
of operations. Specifically it is desired that an
experiment be undertaken to measure the acoustical and
vibrational environment present in the Shuttle payload bay
from prior to Space Shuttle Main Engine (SSME) ignition (at
approximately T-6 seconds) until the Orbiter has exited the
Earth's atmosphere (at approximately T+2 minutes).

Previous GAS missions have been deployed to accomplish
this same mission goal. In these previous missions the
solution to the problem of independent experiment initiation
was addressed by way of a simple sound pressure level (SPL)
sensor used to detect the unmistakable roar of SSME's as
they ignite at T-6 seconds. By this method the sizable
impulse thus generated can easily be used to signal
experiment initiation. In this way power is applied to data
collection and storage elements whose purpose is to record
the information relevant to the mission of the experiment.

The obvious shortcoming in this experimental scheme is
that it uses as its prime mover the very noise and vibration
which it presumes to measure. Though the delay caused by
impulse generation and transmission via the SPL sensor may
be minimal, it nonetheless requires a finite amount of time
for tape transport transients to settle and begin the
recording of meaningful data. This delay has been reported
to be as much as several seconds and so can be seen to be a

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Therefore our task is to develop a matched filter which will detect the presence of a spectral peak at 600 Hz and/or at coincident harmonic multiples of 600 Hz. We will attempt to realize the needed performance emphasizing only the most evident 600 Hz peak. Based upon the results of this design, will then know if we must consider the additional impact of the less evident harmonic elements.

Our desire is to implement the scheme which provides the simplest, smallest, most reliable, and least power consuming design which will ensure APU detection prior to launch. Therefore detection of all higher order harmonic components is less important than the development of a filter which accomplishes the primary goal. We shall examine both analog and digital methods for implementing our matched filter and compare the effectiveness of the various designs before selecting the device which will orbit the Earth.

but for our purposes this is an inconsequential

shortcoming.)

An examination of the PSD's of the remaining sets of

data not corrupted by the lack of TSC reveals the expected

behavior. In all cases the noise background remains

essentially unchanged from the first of the plot pair to the

second except for the effect of the impressed APU signature

clearly evident in the second. In every plot performed

after APU start-up the characteristic 600 Hz peak is evident

to some degree and in many instances we also see the

harmonic components at 1200 and 1800 Hz. This is especially

true for those plots reflecting the environment surrounding

microphone 9403 which is located only a bulkhead removed

from the APU's themselves. However, of some concern is the

fact that the 600 Hz peak is least evident for microphone

9405 which is at the forward bulkhead furthest removed from

the APU's and where it is expected that the GAS canister

will be placed for the upcoming mission.

The salient points are therefore as follows:

1. The APU does provide a specific signature which becomes clearly evident in the audio spectrum of the Shuttle payload bay pre-launch acoustic environment. There are well-defined spectral peaks at a fundamental frequency of 600 Hz and at integral harmonics thereof.

2. The magnitude of the APU signature is variable in the payload bay depending upon the location of the sensor used to detect it. A sensor placed closer to the after bulkhead will be more apt to respond to the APU signature in a manner which will facilitate matched filter performance, but the signature is evident throughout the payload bay.

it is known that measures were taken to minimize the error introduced in the dubbing process. On most copies a Tape Speed Compensation (TSC) process was employed which ensures that the tape transport travels at the same speed as when originally recorded. That this process is indispensable is realized upon examination of the PSD's obtained for microphones 9405 and 9219 on STS-3. In these two cases alone TSC was not employed due to operator error at a previous generation. The noise floor thus generated is seen to be an order of magnitude greater than in other plots and is severe enough to mask the desired information. In all other tape copies TSC was employed.

(Another generation of tape copies was recorded for use at the Naval Postgraduate School in the development of the experiment described earlier. This recording process was accomplished using a Hewlett-Packard Model 3964A Instrumentation Data Recorder in an FM mode to allow recording of analog data from 0 to 8 kHz. The HP recorder also employs a tape speed servo control which also ensures tape speed accuracy. PSD plots were obtained in all cases for the dubbed tape to verify the accuracy of this latest dubbing routine. In each case the PSD of the dubbed data was confirmed to be a good reproduction of the "original" except for the region below 200 Hz. In this region the reproduction was not as good as in the region above 200 Hz

Appendix B is a summary of PSD plots of the acoustic environment present in the Shuttle payload bay at three different locations for the three missions listed in the previous section. As noted in Figure 2.2 the locations of the three microphones are dispersed throughout the payload bay to reveal variations in the acoustic signature from one location to another. Microphone V08Y9405A (which shall be referred to as 9405 for simplicity) was positioned near the forward bulkhead of the payload bay, furthest removed from the APU. Microphone V08Y9219A (9219) was located low and amidships, and microphone V08Y9403A (9403) was located at the after bulkhead, closest of the three to the APU. All three were identically configured to respond to a dynamic range of 110-157 dB.

The payload bay acoustic data is presented in pairs of plots with the first of the pair showing the signature before the APU is turned on and the second showing the signature approximately thirty seconds later after APU start-up. This data was obtained from an analog magnetic tape copy of the original data recording which was made available from the DATE group at Aerospace Corporation headquarters in Los Angeles.

There is doubtless some extraneous noise introduced in the process by which the original tape was copied to yield the tape available at Aerospace. Furthermore, the generation of the Aerospace copies are not known. However

Table 2.1

DEVELOPMENT FLIGHT INSTRUMENTATION (DFI)
ACOUSTIC MEASUREMENT INFORMATION

Microphone Number	Range (dB)	Cargo Bay Location	Orbiter Station Location X	Y	Z
VO8Y9219A	110-157	Internal	863	-100	381
VO8Y9220A	110-157	Internal	1190	0	427
VO8Y9401A	130-177	External	639	3.5	500
VO8Y9402A	130-177	External	1281	4.2	500
VO8Y9403A	110-157	Internal	1306	12.0	400
VO8Y9404A	130-177	External	1296	0	300
VO8Y9405A	110-157	Internal	640	4	423

Note: The frequency response of all microphones is wide-band, 20 Hz to 8 kHz.

D. STS PAYLOAD BAY PRE-LAUNCH ACOUSTIC ENVIRONMENT

As indicated in the previous section we are principally interested in the response of three internal microphones to the Shuttle payload bay environment. The intent is to examine the environment prior to APU start-up to determine the noise background present before the APU acoustic signature is impressed upon this background. Then microphone responses will be examined after APU start-up to reveal the APU acoustic signature over the noise background. Based upon our previous examination of the APU vibrational signature evident in equipment testing we expect to see that spectral peaks at the fundamental and harmonic frequencies of 600 Hz will become clear at the time of APU start-up.

at launch.   Rounding out the array of acoustic sensors were

three additional microphones mounted externally.   All

microphones were manufactured by Gulton Industries with only

minor alterations differentiating the three external sensors

from the four internal ones.   The relative location of each

of these seven acoustic sensors is shown in Figure 2-2.
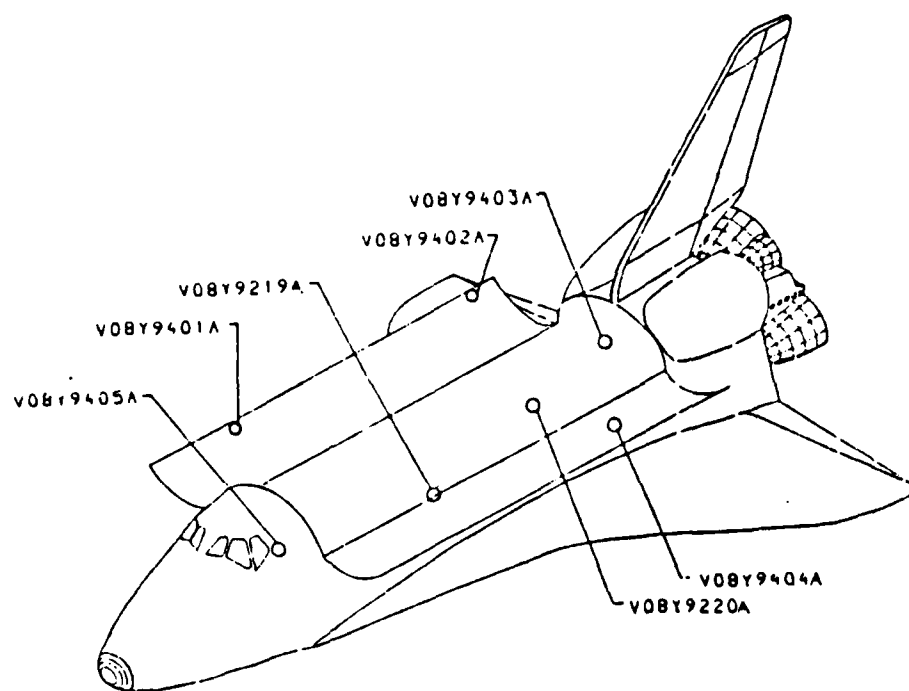
Figure 2.2   DFI Acoustic Measurement Locations

Sensor location designators, dynamic range and frequency

response of each microphone are shown in Table 2-1 on the

following page [Refs. 3 and 4].

C. STS PAYLOAD BAY ACOUSTIC ENVIRONMENT MEASUREMENT INSTRUMENTATION

Data instrumentation recorders were flown on all early Shuttle flights to measure the acoustic environment present during the launch and landing phases of these missions. These experiments were conducted under the auspices of the NASA DATE (Dynamic, Acoustic and Thermal Environments) Working Group which has as its mission the development of improved methods for predicting all aspects of STS (Shuttle Transportation System) payload environments. Pursuant to this study we shall make use of data collected during each of the following three Shuttle missions:

-- STS-2 (conducted November 12-17, 1981)

-- STS-3 (conducted March 22-27, 1982)

-- STS-4 (conducted June 27 - July 4, 1982)

In each of these missions it is only the data which was recorded just prior to the launch which is of any significance for our purposes here.

Of particular interest to us is the acoustic data recorded at three specific locations in the Shuttle payload bay on each of the three flights listed above. On each flight sixteen selected sensors comprised the STS Development Flight Instrumentation (DFI) system. Of these sixteen sensors, four internal microphones were used to measure the acoustic environment present in the payload bay

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of higher spectral components although an expected 2400 Hz peak is present in several plots despite the attenuation.

The significance of these plots is in the consistency of the component spectral elements despite APU loading. Although the relative and absolute magnitudes of the fundamental 600 Hz peak and its harmonic constituents vary somewhat over the range of loading displayed the spectral location of each remains fixed. This shift in magnitudes is of some concern to mechanical engineers as it has been shown that failures in some rotating machinery have occurred when vibration signatures have deviated in this manner. But our concern is with the consistency of the location of the spectral peaks as this confirms the RPM stability of the APU over expected levels of loading.

We thus have a basis for further investigation of the acoustic environment in the Shuttle payload bay. We know that there is a specific vibrational signature which accompanies the normal functioning of the APU and we may expect that this vibration will translate to an acoustic signature in the Shuttle pre-launch environment. We now proceed to investigate this proposition with an examination of the acoustic environment present in the Shuttle payload bay prior to launch.

APU output shaft horsepower is delivered to the hydraulic pump at a nominal 3800 RPM's through a two stage reduction gear. Although balanced to within exceedingly fine tolerances dictated by extremely fast rotational RPM's the APU is nevertheless characterized by a specific vibrational signature. We shall examine this signature in some detail because a careful understanding of its nature is crucial to the development of a filter dedicated to its detection.

In Appendix A there is included a graphical summary of the results of hotfire testing of one APU installed in the Shuttle Orbiter. These are Power Spectral Density (PSD) plots of accelerometers mounted along the x-axis (D0280A) and z-axis (D0281A) of this particular APU for various levels of loading. Also shown for reference is a PSD plot of the background noise prior to APU ignition. Relative to the plots of APU vibration we see that in each case the background noise is no less than two orders of magnitude lower than the PSD peaks of data obtained from the loaded APU.

The results of this test reveal a very particular vibrational signature for the APU. It should be noted that there are consistently repeating peaks at 600 Hz and two harmonics above this value at 1200 Hz and 1800 Hz. The bandwidth of the filter employed in this investigation had a 3 dB rolloff at 2300 Hz. This obviated a close examination

APU MISSION DUTY CYCLE

81.1 MINUTE TIME LINE
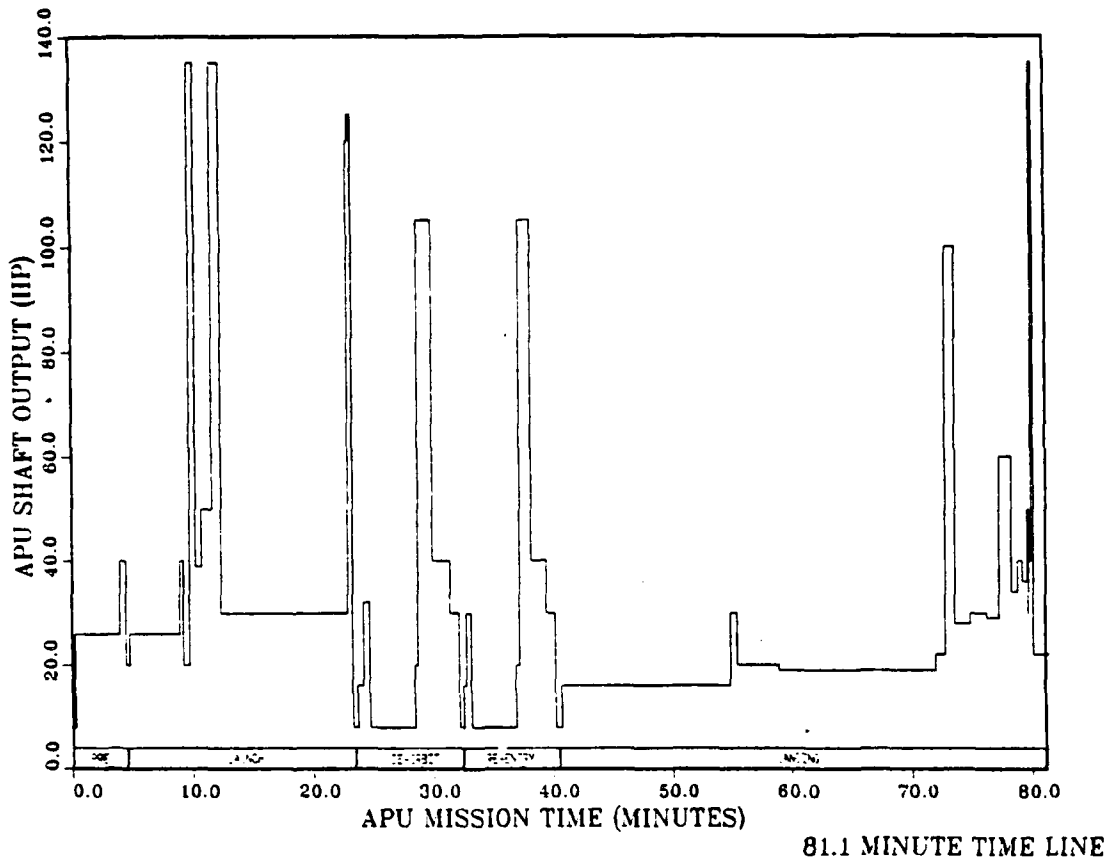
**Figure 2.1   APU Mission Duty Cycle
(Baseline 81.1 Minute Time Line)**

In the pre-launch phase APU loading varies minimally

from 8.0 to 40.0 horsepower according to hydraulic

requirements during the phase.   Because the APU is designed

to operate at 72,000 RPM's (plus or minus eight percent)

over its entire range of output shaft horsepower, its steady

state and dynamic vibrational characteristics vary little

during the pre-launch phase.   This is due to the minimal

hydraulic loading which characterizes this phase.

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II. THE AUXILIARY POWER UNIT (APU) AND THE SHUTTLE PAYLOAD BAY PRE-LAUNCH ACOUSTIC ENVIRONMENT

A. APU DESCRIPTION

The Auxiliary Power Unit (APU) was developed by the Sundstrand Corporation under contract from Rockwell International, the prime contractor for the Space Shuttle. Each Shuttle Orbiter is equipped with three complete APU's and associated hydraulic systems. Each APU and its hydrazine fuel system is independent of the other two during normal operations. However, there are cross-ties between hydraulic systems which allow any two APU's to pick up the load from a third should it fail during operation.

B. APU MISSION DUTY CYCLE

Figure 2.1 is a representative diagram of a typical APU Mission Duty Cycle for an entire Shuttle mission [Ref. 2]. It is expected that a minimum of two restarts from a cold condition will be typical in a mission. The baseline duty cycle calls for 81.1 minutes of APU operation at various power levels from 8.0 horsepower to its maximum rated 135.0 horsepower. This includes launch, de-orbit, re-entry and landing phases and so includes operation at all altitudes corresponding to extremes of airfoil atmospheric resistance and Orbiter speed.

Several different schemes for accomplishing a matched band-pass filter design will be discussed. Nominally this will include an analog design built around operational amplifiers and a digital design of Infinite Impulse Response (IIR) implemented with an INTEL 2920 Signal Processor. This latter configuration will be derived from a cascaded IIR design which results from the Bilinear transformation of the analog filter. The difference equation representation of the digital filter transfer function will form the basis for the 2920 design. In addition I will discuss further design alternatives including an Adaptive Finite Impulse Response (FIR) Weiner filter and an idea for a design centered about a speech processing algorithm. Advantages and disadvantages of each approach will be discussed.

Ultimately one design will be chosen for integration within the GAS experiment just described and scheduled for launch in an upcoming Shuttle mission.

T-5 minutes. These units are essentially jet engines which provide for hydraulic power of Shuttle airfoil control surfaces during the atmospheric phases of launch and landing. They are designed to operate at very high (72,000) RPM's, but also generate a very specific acoustic signature in the audio range of the spectrum during normal operation. If it is possible to detect this APU acoustic signature during the pre-launch sequence of events and to discriminate this signature from among the various other acoustic events which may also occur during the pre-launch phase, then it may be possible to signal experiment initiation by detection of this event.

The emphasis of this thesis will be to describe the nature of the APU acoustic signature and to develop a matched filter which is tuned to its characteristics. It should be emphasized from the beginning that this it is not my intention to develop a classical "matched filter" which rigorously conforms to that definition. I do not have the uncontaminated APU acoustic signature data at my disposal which would allow that sort of an analysis. Rather it is my intention to examine the APU signature in the Shuttle cargo bay environment and to develop a filter which is "matched" to that contaminated signature. It is expected that an extremely narrow (high Q) band-pass filter will accomplish this goal.

significant gap in any serious analysis of the acoustical and vibrational transients which must accompany ignition and launch.

One means of lessening the impact of transient delay is to substitute a solid state data recorder for the traditional magnetic tape variety of instrumentation data recorders. This idea is being investigated by another team of researchers at the Naval Postgraduate School for incorporation into a deployable GAS mission canister. Despite the advantage which a solid state recorder will afford toward minimizing the transient delay prior to meaningful data collection, it can never completely eliminate the transient effect which accompanies any scheme which is trying to measure the same signal which it also uses for experiment initiation. There is a causal imperative here which is inescapable.

It is the purpose of this thesis then to develop a means of experiment initiation which will allow data collection to commence well before SSME ignition. In this manner we will be allowed a full measure of the acoustical and vibrational environment which is present in the Shuttle payload bay during launch.

C. DISCUSSION OF THE GENERAL SOLUTION ALGORITHM

The timeline of Shuttle events prior to launch includes the turn-on of Auxiliary Power Units (APU) at approximately

III. <u>ANALOG FILTER DESIGN THEORY AND IMPLEMENTATION</u>

The traditional method of filter implementation in
electronic circuitry was for a long time characterized by an
implementation of passive and discrete resistive, inductive
and capacitive components tuned to respond to the desired
frequency components of the input signal. In the earlier
years of circuit design this procedure involved a lengthy
process of theoretical development and precise component
selection. This was often a tedious process involving
component trial and substitution.

Analog filter design took a great leap forward with the
advent of integrated operational amplifiers (op-amps) and
later, integrated circuit (IC) technology. Now for
instance, using an integrated circuit such as the National
Semiconductor AF100 Universal Active Filter as a design
basis, it is possible for a circuit designer to construct a
precise analog filter circuit with a surprising economy of
effort. We will use the Biquad Elliptic Filter design which
forms the basis of the AF100 to implement the analog designs
we shall develop herein.

A. PRACTICAL DEVELOPMENT OF AN ANALOG BAND-PASS FILTER

We will begin our development of a tuned filter design
by examining an analog IC implementation of a band-pass

filter with a center frequency of 600 Hz. (We could expand this band coverage to include the two additional center frequencies of 1200 Hz and 1800 Hz if it proves that such a design modification is necessary.) In this development we shall choose to build an Elliptic (or Cauer) filter which exhibits a much steeper roll-off outside the passband over a Butterworth or Chebyshev design of equivalent order. The disadvantage of ripple in the passband, which characterizes Elliptic filters, will cause minimal impact and will not be a factor in the realization of our goal. In fact we can allow the ripple in the passband to be relatively high because our intent is not to pass a faithful representation of the APU signature but only to detect its presence. Thus our goal is to construct a band-pass filter with a high quality factor and narrow passband. This corresponds to a steep roll-off out of the passband.

The method which will be employed to realize this band-pass filter will be to describe the characteristics of the desired analog band-pass design and, using a low-pass-to-band-pass transformation, solve for the form of the corresponding low-pass prototype using transform relations. This will allow us to determine the necessary order of the low-pass design which can subsequently be transformed into the required band-pass filter.

If we again examine the PSD plots of the APU noise above the background for the 600 Hz component we can generalize a

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desired filter transfer function to approximate this response. Let us choose the 3 dB points of the band-pass filter (centered at 600 Hz) to be at 575 and 625 Hz. We will allow the pass-band ripple width (PRW) to be as much as 2 dB within the pass-band. Let us furthermore require the stop-band attenuation on either side of the pass-band to be down at least 30 dB at 500 and 700 Hz. This represents a very steep roll-off characteristic and suggests the use of an Elliptic filter design for that reason. In fact, to achieve this degree of roll-off in a low-pass design would require a model prototype of order 6. The equivalent Chebyshev design would require a minimum order of 14, while the Butterworth low-pass filter equivalent order would be at least 63. Clearly the Elliptic design is our only viable alternative.

The low-pass to band-pass transformation for analog filters results in a transfer function which raises the order of the low-pass equivalent by a factor of two. Therefore if we design a band-pass filter it will necessarily consist of a number of second-order stages in the final implementation.

1. Low-Pass to Band-Pass Frequency Transformation

In order to develop the transfer function of an appropriate analog band-pass filter we must begin with the transfer function of the corresponding analog low-pass filter which may be transformed into the desired band-pass

filter by a frequency transformation. However, the
characteristics of our final filter are known in band-pass
form. Thus we must deduce the analog low-pass design from
the band-pass characteristics and then apply the analog
transformation to the low-pass prototype to realize our
goal. This development is a combination of procedures
described in Chen [Ref. 5] and Johnson [Ref. 6].

We wish to design an analog band-pass filter having
the following characteristics

f'_{p_2} = 575 Hz

f'_{q_2} = 500 Hz .

f'_{p_1} = 625 Hz

f'_{q_1} = 700 Hz

PRW = 2.0 dB (allowable ripple in the passband)

MSL = 30 dB (minimum attenuation in stop-band)

In this analog development the prime frequencies
refer to the band-pass function and the unprimed frequencies
to the low-pass function. Figure 3.1 is a graphical
depiction of the relationship between the transfer function
transform pair. The negative axis frequencies arise from
the mathematics of this development. However, we shall only
be functionally concerned with the positive axis
transformation. We are also considering the low-pass
function to be normalized (ω = 1).

$|H(\omega)|$

$-\omega_q$ $-\omega_p$ 0 ω_p ω_q ω

$|H'(\omega')|$

$-\omega'_{q1}$ $-\omega'_{p1}$ 0 ω'_{q2} ω'_{p2} ω'_{p1} ω'_{q1} ω'
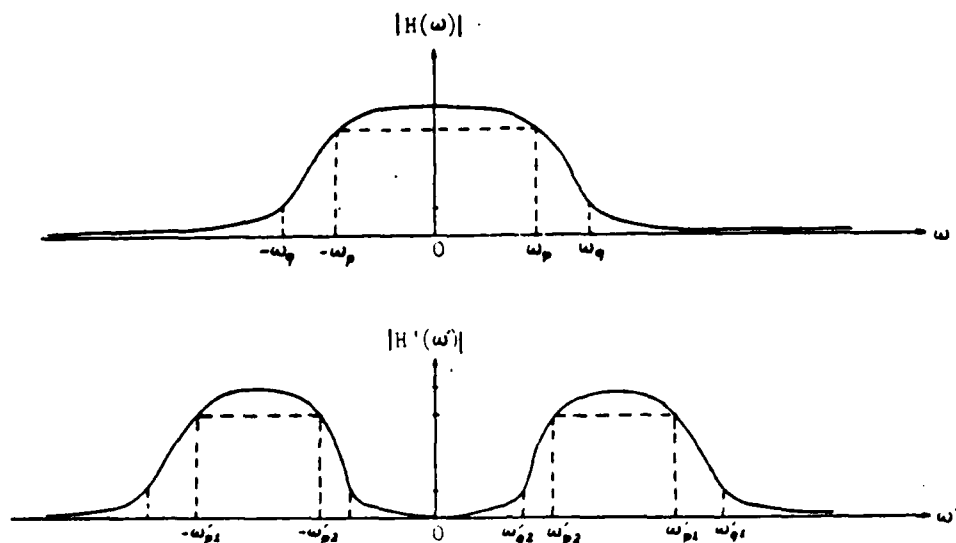
Figure 3.1   A Low-Pass to Band-Pass Frequency
Transformation in the Analog Domain

A suitable transformation must therefore accomplish

the transform relations detailed in Table 3.1 [Ref. 5].

Table 3.1

LOW-PASS TO BAND-PASS TRANSFORM PAIRS

Low-Pass Function	Band-Pass Function
$\omega = \infty$	$\omega' = \infty$
$\omega = 1$	$\omega' = \omega'_{p1}$
$\omega = -1$	$\omega' = \omega'_{p2}$
$\omega = -\infty$	$\omega' = 0$

As developed in Chen [Ref. 5: p. 235], the analog

frequency transformation which will accomplish a low-pass to

band-pass frequency transformation [H(s) ==> H(s')] is given

by the following relation.

$$s = \frac{s'^2 + \omega'_{p_1}\omega'_{p_2}}{s'(\omega'_{p_1} + \omega'_{p_2})}$$

or if we substitute the above values

$$s = \frac{s'^2 + 4\pi^2 \cdot (3.59375 \times 10^5)}{s' \cdot 2\pi \cdot 50}$$

or, using $s = j\omega$

$$\omega = -\frac{4\pi^2 \cdot (3.59375 \times 10^5) - \omega'^2}{\omega' \cdot 2\pi \cdot 50}$$

Making the following substitutions into the preceding equation yields

$\omega'_{q_1} = 2\pi \cdot 500$

$\quad ==> \omega_{q_1} = -4.3750000$

and

$\omega'_{q_2} = 2\pi \cdot 700$

$\quad ==> \omega_{q_2} = -3.7321429$

Therefore we are left with the need to design an analog low-pass filter with

$\omega_c = 1$ rad/sec, and

$\omega_q = 3.7321429$ rad/sec

This leaves us with a normalized low-pass transition width (TW_{lp}) of

$$TW_{lp} = \omega_q - \omega_c$$

$$= 2.7321429$$

We now have enough information to enter the tables in Johnson [Ref. 6] to obtain the data shown in Table 3.2.

Table 3.2

ELLIPTIC LOW-PASS FILTER DATA
(for the band-pass filter low-pass prototype)

A	B	C	WZ	WM	KM
21.16400	0.787152	0.842554	4.600435	0.715610	1.258925

2. 600 Hz Elliptic Band-Pass Filter Design

In the case of elliptic band-pass filters the transfer function may be factored into the product of second-order functions. The two factors arising from each second-order low-pass stage have the forms [Ref 6: p. 100]

$$\left[\frac{V_2}{V_1}\right]_1 = \frac{K_1\sqrt{C/A}(s^2 + A_1\omega_0^2)}{s^2 + (D\omega_0/E)s + D^2\omega_0^2} \qquad 3.1$$

and

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$$\left[\frac{V_2}{V_1}\right]_2 = \frac{K_2\sqrt{C/A}(s^2 + \omega_0^2/A_1)}{s^2 + (\omega_0/DE)s + \omega_0^2/D^2)} \qquad\qquad 3.2$$

where

$$E = \frac{1}{B}\sqrt{\frac{C + 4Q^2 + \sqrt{(C + 4Q^2)^2 - (2BQ)^2}}{2}}$$

$$D = \frac{1}{2}\left[\frac{BE}{Q} + \sqrt{\frac{(BE)^2}{(Q)^2} - 4}\right]$$

and

$$A_1 = 1 + \frac{1}{2Q^2}(A + \sqrt{A^2 + 4AQ^2})$$

and $Q = f_0/BW = 600/50 = 12$. The coefficients A, B
and C are those of the normalized low-pass function given
in Table 3.2 above, and K_1 and K_2 are related to
the stage gain K by $K = K_1K_2$.

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Equations 3.1 and 3.2 above are of the general form

$$\frac{V_2}{V_1} = \frac{\rho(s^2 + \alpha\omega_0^2)}{s^2 + \beta\omega_0 s + \gamma\omega_0^2}$$

3.3

which is identical to the form of the low-pass transfer
function, except for the replacement of ω_0 by the
corresponding low-pass term ω_c.

Our analog band-pass filter will have two stages of
the form given by Eq. 3.3. Comparing Eq. 3.3 with Eq. 3.1
and Eq. 3.2 reveals the following transfer function
coefficients of the band-pass filter stages [Ref 6: p. 118]:

1) First stage

$\rho = K_1 \sqrt{C/A}$

$\alpha = A_1$

$\beta = D/E$

$\gamma = D^2$

2) Second stage

$\rho = K_2 \sqrt{C/A}$

$\alpha = 1/A_1$

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$$\beta = 1/DE$$

$$\gamma = 1/D^2$$

In the FORTRAN program ABPDBP (included as Appendix C) many of the calculations which are indicated in this thesis development will be performed. In Section 1 of this program we begin with desired filter parameters and tabulated values which correspond to the filter we wish to build. We then calculate several derived parameters from these initial values. Next we perform further calculations (which shall be developed shortly) which yield values for filter resistors and capacitors.

In Section 2 of ABPDBP we use the two sets of filter parameters which correspond to each of the filter stages indicated by Eq 3.3 to arrive at the overall transfer function. ABPDBP describes the corrections which must be made to provide for pre-warping of frequencies preparatory to a digital transformation (which shall be discussed in Chapter 4) but these changes can be ignored in this analog discussion. Thus we will use f_0 = 600 Hz (which implies the use of WO, not WODIG) in the program calculations. The fourth order analog filter transfer function which results from this development is given in Equation 3.4.

$$H(s) = \frac{a_0 s^4 + a_1 s^3 + a_2 s^2 + a_3 s + a_4}{b_0 s^4 + b_1 s^3 + b_2 s^2 + b_3 s + b_4}$$ 3.4

The values of the coefficients in this analog transfer function representation are given in Table 3.3 which follows.

Table 3.3

ANALOG ELLIPTIC BPF FOURTH ORDER COEFFICIENTS
(Normalized coefficients with gain 0.03981)

Coefficient	Value
a_0	1.0000
a_1	0.0
a_2	2.9587×10^7
a_3	0.0
a_4	1.8991×10^{14}
b_0	1.0000
b_1	2.4351×10^2
b_2	2.7642×10^7
b_3	3.3558×10^9
b_4	1.8991×10^{14}

In Section 2A of the program ABPDBP the poles and zeros of the analog transfer function are then calculated to demonstrate the stability of the filter design. The values for the poles and zeros may be observed in the output of ABPDBP and are reproduced graphically in Figure 3.2 on the following page. The poles of the filter lie within the left

half of the s-plane and this confirms the stability of our design.

3. Analog Band-Pass Filter Simulation

Now that we have developed the transfer function which describes the desired analog band-pass filter we can use this function to simulate the active operation of the

POLE/ZERO PLOT FOR ANALOG ELLIPTIC BPF
(NOTE SCALE DIFFERENCE)
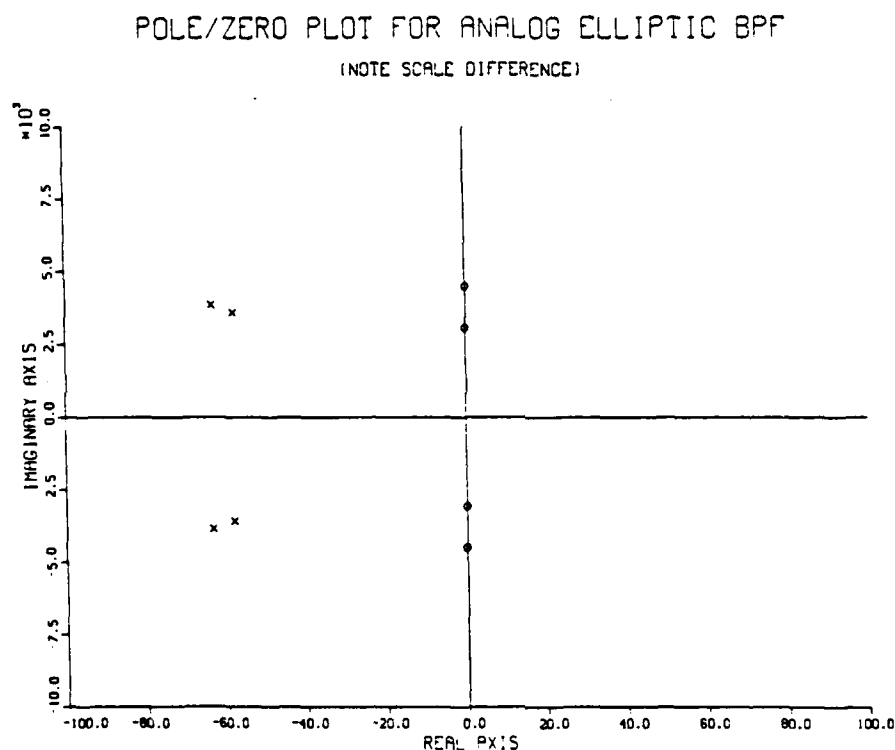
Figure 3.2   Pole/Zero Plot for the Analog Elliptic
Band-Pass Filter

filter.   The FORTRAN program ABPFR (which is included as Appendix D to this thesis) is used to examine this particular band-pass filter simulation.   Figures 3.3, 3.4

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and 3.5 which follow are the results of this computer

simulation of the filter response for the device we have

just designed. The range of frequencies of the simulated

computer input is DC to 1 kHz. The simulated amplitude is

constant over the range of input frequencies.

In Figure 3.3 we see the amplitude response which is

near zero at all but the passband frequencies around 600 Hz.

Between 500 and 700 Hz we confirm the desired filter

response. The center frequency is located at 600 Hz and

ANALOG ELLIPTIC BPF FREQUENCY RESPONSE

AMPLITUDE VS FREQ (FC-600 HZ)
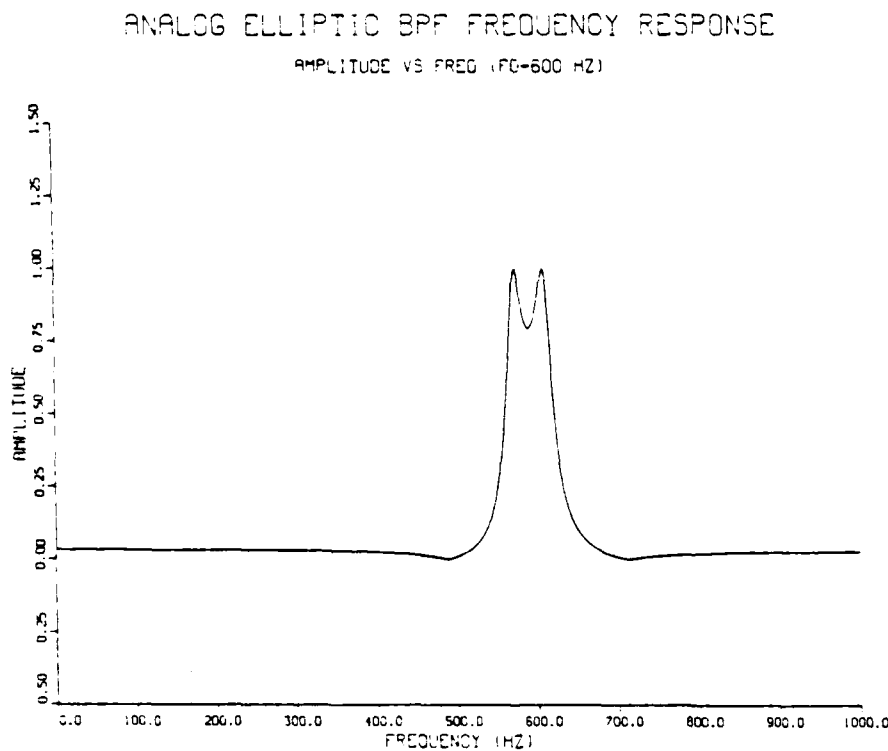
Figure 3.3   Analog Elliptic BPF Frequency Response
(Computer Simulated Amplitude Response)

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there is a significant minimum at the center frequency due
to the effect of the passband ripple of 2.0 dB. Furthermore
we observe a half power point (3.0 dB down point) at about
575 Hz and 625 Hz as specified in our design.

In Figure 3.4 we again observe a computer simulation
of the amplitude response of the filter, this time measured
in decibels. The marked presence of notches at about 500 Hz
and 700 Hz is obvious, and the 30 dB minimum loss in the
stopband is also confirmed. We also have graphical
confirmation of the 2.0 dB ripple width in the passband.

ANALOG ELLIPTIC BPF FREQUENCY RESPONSE
AMPLITUDE (DB) VS FREQ (F0=600 HZ)
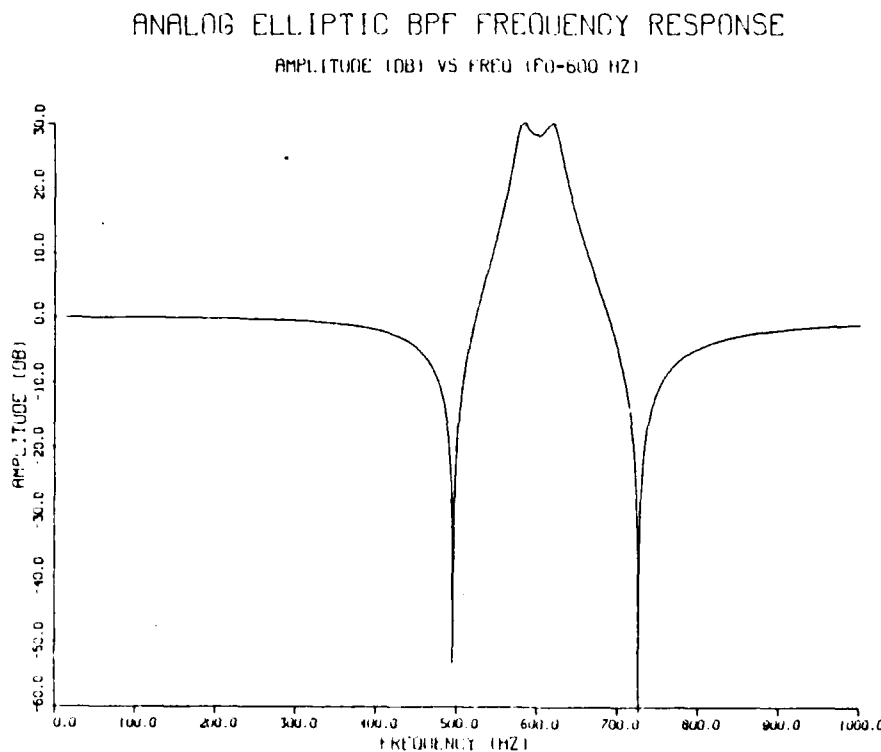
Figure 3.4 Analog Elliptic BPF Frequency Response
(Computer Simulated Amplitude Response in dB)

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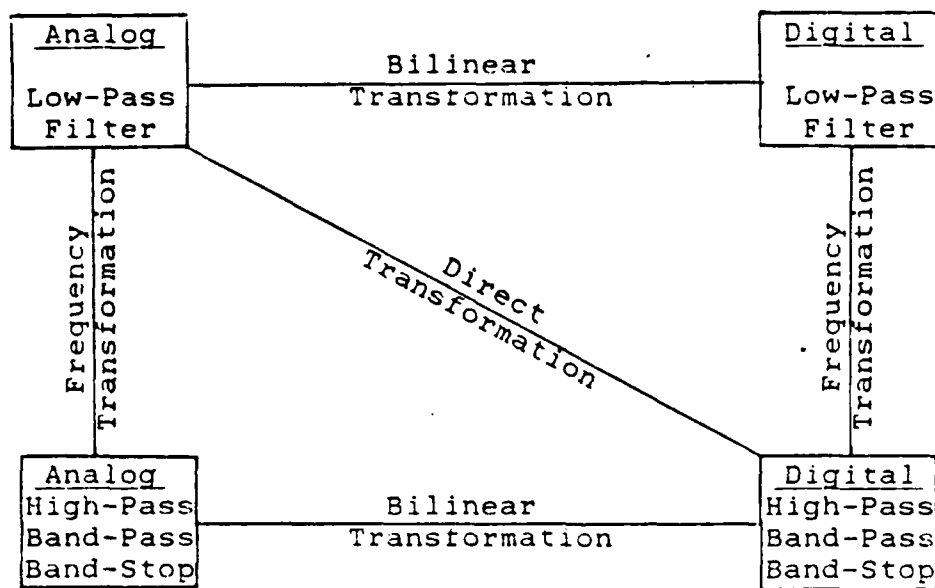
Figure 4.1 Analog and Digital Frequency Transformations

It should be reiterated that our goal in this section will be to develop a digital filter of Infinite Impulse Response (IIR) characteristics. This means that our filter will use the results of previous outputs to realize a later output. Although Finite Impulse Response (FIR) digital filters offer several qualitative advantages over IIR designs in the areas of phase linearity, stability, and an inherent protection against round-off error, they also require a larger number of delay elements to realize a design with a steep filter roll-off. This will be of concern to us when we realize an implementation in hardware with devices limited to a relative few number of filter transfer function poles and zeros.

case known analog filter characteristics in the frequency domain (the Laplacian "s" domain) are converted to similar characteristics in the digital "z" domain. Each of these techniques introduces a non-linearity into the resulting amplitude and phase characteristics of the original analog filter. If necessary to preserve the phase, equalizers may be employed to return the phase characteristic to a nearly linear behavior over the region of interest in the digital domain. In our case any phase distortion can be ignored because we are only interested in frequency detection and not accurate reproduction.

Generally speaking, when beginning with an analog low-pass design, we may proceed in a number of ways to arrive at a corresponding digital band-pass filter realization. For instance, we may first transform the low-pass filter to an analog band-pass design (as we did in Chapter 3 for the low-pass to band-pass transformation) and then employ an analog to digital transformation to yield the digital filter. Alternatively we may choose to employ the analog to digital transform on the low-pass filter and then apply a digital low-pass to digital band-pass transformation to realize our goal. Finally, it is also possible to combine these two-step routines into a single-step analog low-pass to digital band-pass direct transformation. These options are shown in Figure 4.1 [Ref. 5: p. 269].

IV. DIGITAL FILTER DESIGN

When designing an IIR digital filter for a specific application it is common practice to first develop an analog filter with appropriate characteristics as we did in the preceding chapter. Once the analog design is attained it is then possible to transform this analog filter into a digital filter with the desired passband characteristics.

There are several reasons why it is desirable to use this approach [Ref. 7: p. 5-7]. Of primary importance is the fact that the art of analog filter design is highly advanced. Consequently there are many techniques available for implementing specific designs. Because useful results can be achieved, following established analog design procedures presents advantages in the amount of effort which must be spent in the design phase.

Additionally, many useful analog design methods have relatively simple closed-form design formulas. This greatly facilitates the implementation of the corresponding digital filters.

Finally, in many applications it is of interest to use a digital filter to simulate the performance of an analog linear time-invariant filter.

There are many alternative methods for accomplishing a transformation of fixed filter characteristics. In each

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In Figure 3.10 we examine this response more specifically for discrete frequencies in the range of 500 Hz to 700 Hz. Instead of applying a ramped sinusoid we input five discrete sinusoids while maintaining a constant amplitude. Thus we again observe the very narrow bandpass filter response at least within the limits presented here. We also confirm the rapid shift in phase of 180 degrees from the lower to the upper bound in agreement with theory. While this examination by itself does not confirm the desired filter response, it does so when considered with the results of the previous figure.

In Chapter 4 we will use the results of this analog filter implementation to develop an equivalent digital realization. To do this we will use common transformation techniques to arrive at a z-domain transfer function which we will then reduce to a difference equation. This format will then allow us to realize a digital elliptic filter by use of the INTEL 2920 Signal Processor. This hardware realization of the digital filter will be accomplished in Chapter 5.
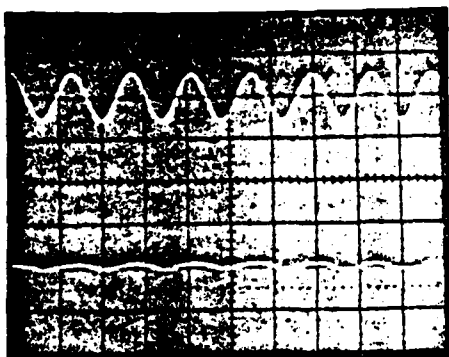
a) 500 Hz
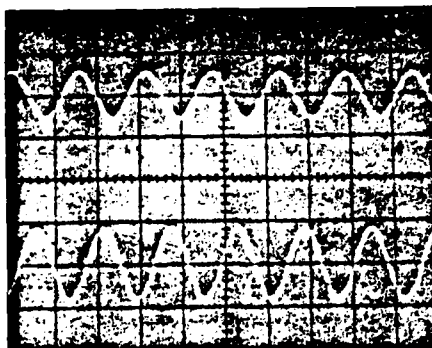
b) 575 Hz
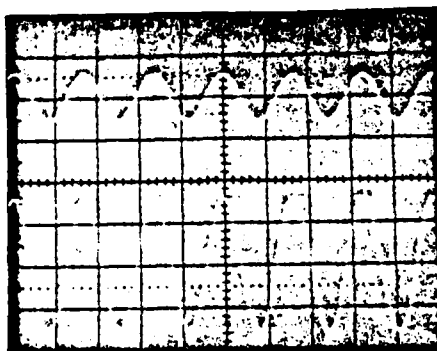
c) 600 Hz
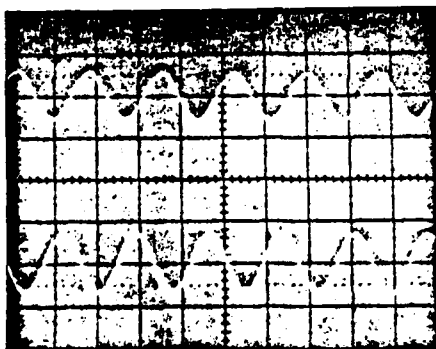
a) 625 Hz
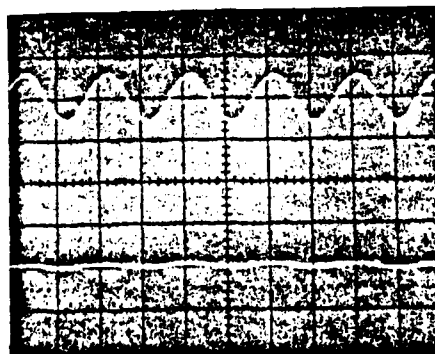
b) 700 Hz

Figure 3.10   Analog Elliptic BPF Frequency Response
Upper trace (Input):   50 mV/div scale
Lower trace (Output): 1.0 V/div scale
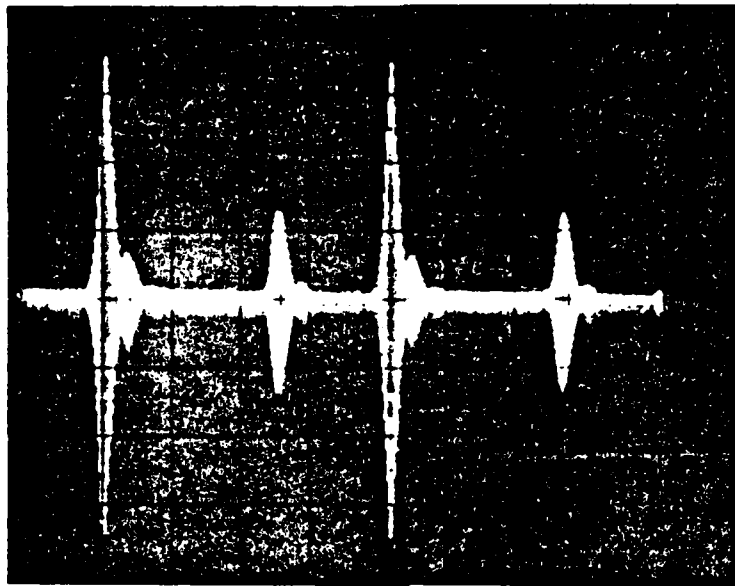
Figure 3.9   Analog Elliptic BPF Frequency Response
(Photograph of Actual Filter Amplitude Response
to a Ramped Sinusoidal Input)

This gives rise to the appearance of a double response which
is noted in the figure.   Actually we are observing a
multiple reponse over successive up and (faster) down ramps
of the input sinusoid.   Thus we are able to observe
graphical confirmation of the filter amplitude response
predicted in the foregoing discussion.

As expected we observe a very narrow filter bandpass
response (with frequency limits we will look at more closely
in the following paragraph).   The curious extended response
("hump") at the upper end of the passband is due to the
inexact placement of poles and zeroes accomplished by tuning
of the filter response in the aforementioned manner.

The two 74161 counter stages which follow the multivibrator are designed to count up to 255 occasions of the threshold being exceeded in a .5 second period before the decision is made that a valid 600 Hz signal was detected. This is an arbitrary figure. The .5 second period is established by the 555 timer which is also fed by the one-shot multivibrator. If the counter stages do not sum to 255 within a .5 second period then the 555 resets the counter stages to zero and counting begins anew with the comparator. If the counter does reach 255 within the .5 second period then a latch is set for the remainder of the .5 second period. This TTL level signal is the one which provides the microprocessor interrupt indicating that the APU signal has been detected.

C. ANALOG BAND-PASS FILTER IMPLEMENTATION RESULTS

Figure 3.9 on the following page is a photograph of the actual frequency response of the analog elliptic band-pass filter we have developed. A sweep generator was used to input a ramped sinusoidal input comprised of a linear continuum of frequencies (generated by application of a skewed triangular input to a voltage controlled frequency oscillator) in the range of approximately 100-1000 Hz. Because the ramp generator does not exhibit an instantaneous return, the return also generates a down-frequency response albeit at a rate greater than that of the up-frequency ramp.

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which follow the amplifier. If the amplitude of the
amplified filter output goes above the threshold set at the
reference input of the LM311-based comparator then a pulse
is developed for the duration that the input signal exceeds
the threshold level. A negative-edge triggered 74121-based
one-shot multivibrator follows the comparator. It is
designed to send a one millisecond pulse to the counter
stages which follow any time the comparator detects an input
signal which exceeds the threshold level.
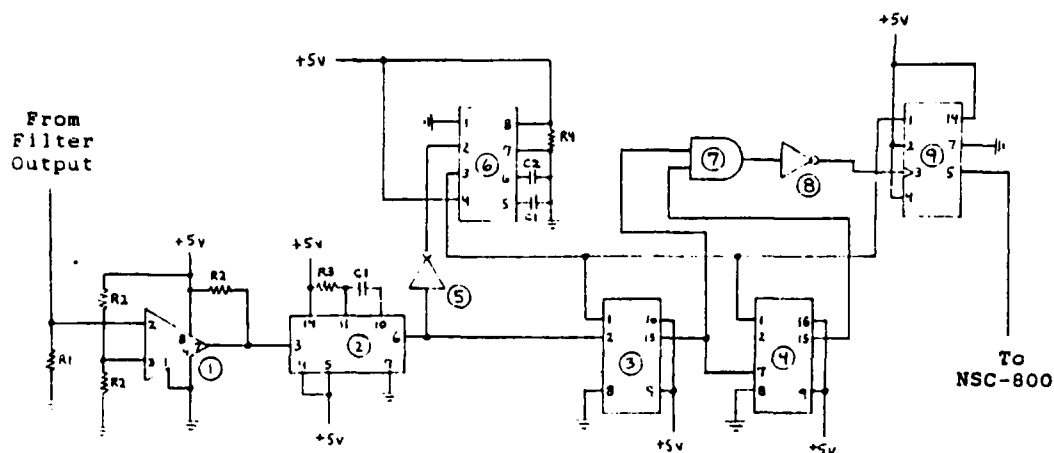
Figure 3.8 Follow-Up Pulse-Shaping Logic Circuitry

Microcircuits	Components
1: LM311 Op-Amp	R1: 100 kΩ
2: 74121 1 msec One-Shot	R2: 20 kΩ
3: 74161 4 Stage Counter	R3: 15 kΩ
4: 74161 4 Stage Counter	R4: 470 kΩ
5: 7404 Inverter	C1: 0.1 μF
6: 555 0.5 sec Timer	C2: 1.0 μF
7: 7432 AND Gate	
8: 7404 Inverter	
9: 7474 D-Type Flip-Flop	

First Stage   Second Stage
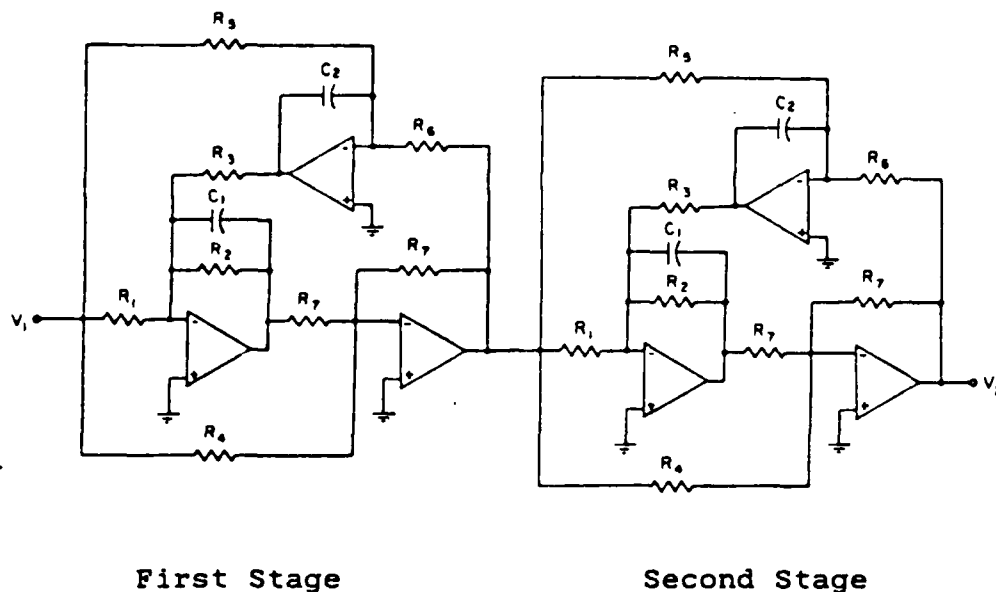
Figure 3.7 Biquad Elliptic Band-Pass Filter Circuit

sinusoidal nature and inadequate to drive a microprocessor

interrupt designed to accommodate TTL logic levels. Thus we

must include further circuitry into our design which will

send a TTL compatible logical signal to the microprocessor

when the APU signal is detected. The circuit which

accomplishes this is shown in Figure 3.8.

The output from the filter stages is first sent to a

linear amplifier constructed around a 741 op-amp. Because

the APU signal is low voltage out of the microphone detector

it is necessary to amplify the filter output prior to

logical evaluation.

The decision of whether or not a 600 Hz component is

present is the function of comparator and counter elements

possible to these values and then tuning the circuit for the desired performance. Tuning is accomplished in each stage by adjusting R_4 to set the notch frequency f_z, R_3 to set the center frequency f_0, R_2 to set Q, and R_1 or R_5 to set the gain.

Table 3.4

BIQUAD ELLIPTIC BAND-PASS FILTER COMPONENT VALUES

1st Stage		2nd Stage	
Component	Value	Component	Value
C_1	.00996	C_1	.01030
C_2	.00995	C_2	.01034
R_7	26.7	R_7	26.7
R_6	25.7	R_6	26.5
R_5	10.5	R_5	20.2
R_4	14.8	R_4	14.8
R_3	25.7	R_3	26.6
R_2	785.	R_2	813.
R_1	437.	R_1	452.

Note: Capacitor values are μF, resistor values are $k\Omega$.

The resulting schematic for the fourth-order Biquad elliptic band-pass filter is shown in Figure 3.7.

2. Follow-Up Logic Circuitry

When the band-pass filter is implemented the effect is to produce a response which narrowly limits the passband to within a few tens of hertz about the center frequency of 600 Hz. Still, the output of this filter will be of

Similarly, the second stage values are given by

$$R_1 = \frac{DE\sqrt{A/C}}{K\omega_o C_1}$$

$$R_2 = KR_1\sqrt{C/A}$$

$$R_3 = \frac{D}{\omega_o C_1}$$

$$R_4 = \frac{A}{C}\sqrt{R_7/K}$$

$$R_5 = \frac{A_1\sqrt{A/C}}{KD\omega_o C_2}$$

$$R_6 = \frac{C_1 R_3}{C_2}$$

In Section 1 of the program ABPDBP (introduced as Appendix C) we calculate the resistor values for the Biquad band-pass circuit just discussed. The resulting component values which were thus derived are shown in the appendix and are also included here as Table 3.4. These are computed values for resistance and capacitance. In fact the circuit is constructed by selecting standard values as close as

coefficients and the derived complements we have already
evaluated. We begin our development by choosing a standard
value for C_1 (given roughly by $10/f_o$ μF) and
then proceeding to calculate elemental values. In the
equations which follow the values for C_2 and R_7
are arbitrary within limits, and are chosen to minimize the
spread of resistance values. We pick $C_2 = C_1$ and
$R_7 \approx 1/(\omega_o C_1)$. A_1, E and D are as given previously.

The first stage values are thus [Ref. 6: p. 126]:

$$R_1 = \frac{E\sqrt{A/C}}{KD\omega_o C_1}$$

$$R_2 = KR_1\sqrt{C/A}$$

$$R_3 = \frac{1}{D\omega_o C_1}$$

$$R_4 = \frac{A}{C}\sqrt{R_7/K}$$

$$R_5 = \frac{D\sqrt{A/C}}{KA_1\omega_o C_2}$$

$$R_6 = \frac{C_1 R_3}{C_2}$$

B. HARDWARE IMPLEMENTATION

1. Biquad Analog Band-Pass Elliptic Filter

There are many ways to perform a hardware implementation of the analog band-pass transfer function we have just developed. One relatively easy method employs the use of op-amps as the active filter component. We shall use a Biquad op-amp filter implementation which exhibits good stability and ease of tuning. Additionally, implementation is made simpler by the use of a 74124 quad op-amp microchip which allows a single chip per second-order stage. The generalized circuit diagram for a second-order stage of a Biquad filter is shown in Figure 3.6 [Ref. 6: p. 127].
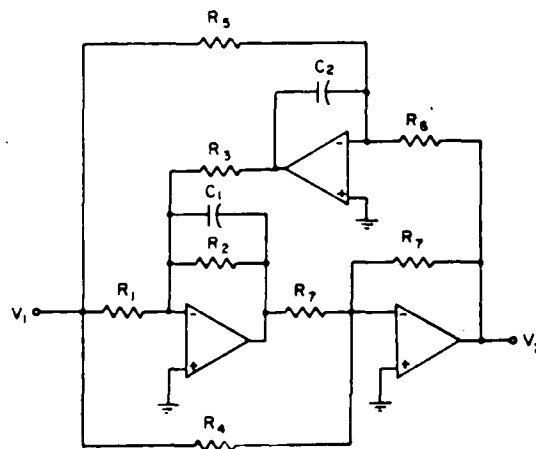
Figure 3.6 Biquad Elliptic Filter Circuit

Component resistor and capacitor values for the Biquad filter depend upon the low-pass normalized

Finally, in Figure 3.5 we view the computer
simulation of the analog filter phase response. Although
our application is not phase dependent (due to the fact that
it is the presence alone of the 600 Hz element which is of
concern to our circuit--not its accurate transmission), we
do confirm the significant effect upon phase for our
elliptic filter in the passband between 500 Hz and 700 Hz.
Between these two frequencies we observe a 360 degree shift
in phase.

ANALOG ELLIPTIC BPF PHASE RESPONSE

PHASE VS FREO (FO-600 HZ)
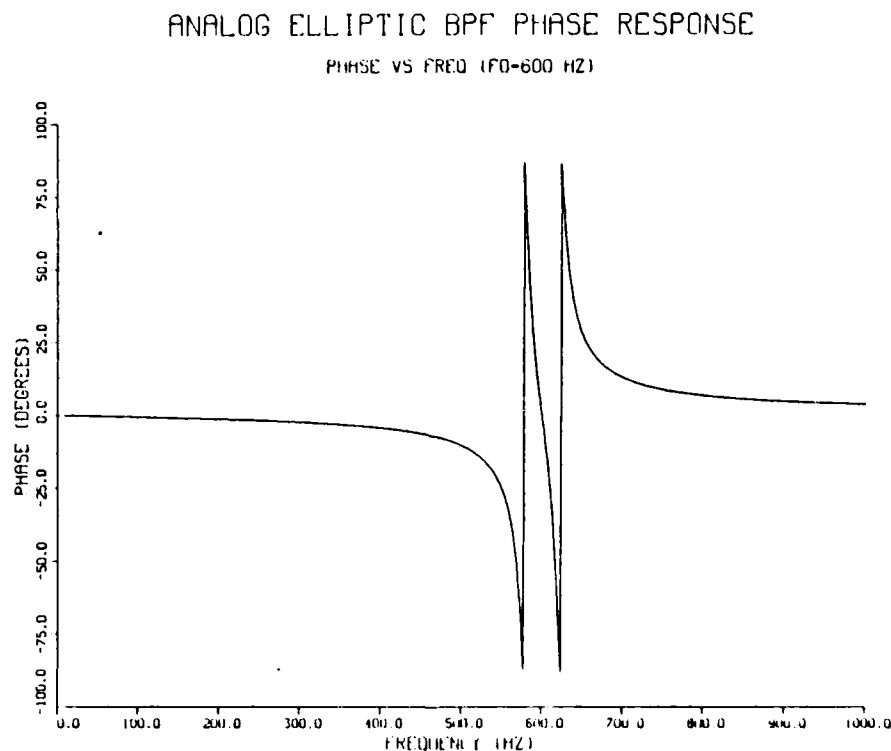
Figure 3.5 Analog Elliptic BPF Frequency Response
(Computer Simulated Phase Response)

A. ANALOG BAND-PASS TO DIGITAL BAND-PASS FILTER DESIGN

An analog-to-digital bilinear transformation makes it possible to apply a relation which transforms an analog band-pass filter into a desired band-pass digital design.

We will realize the 600 Hz digital bandpass filter by applying the bilinear transformation to the transfer function of the analog band-pass filter we developed in Chapter 3. Once implemented we will examine the performance of this filter in view of our goal of APU start-up identification. If necessary we will determine which refinements and modifications to our design may be necessary to realize our goal.

We recall from Chapter 3 that the transfer function of the analog elliptic band-pass filter was given by the product of the two second-order functions given by Eqs. 3.1 and 3.2. This product has been computed (as shown in Appendix C) and is found to be

$$\frac{V_2}{V_2} = \frac{\rho(s^4 + Fs^3 + Gs^2 + Hs + J)}{s^4 + Ms^3 + Ns^2 + Ps + Q}$$

where

$\rho = 0.039811$

$F = 0$

$G = 29.587 \times 10^6$

$$H = 0$$

$$J = 189.91 \times 10^{12}$$

$$M = 0.24351 \times 10^{3}$$

$$N = 27.642 \times 10^{6}$$

$$P = 3.3558 \times 10^{9}$$

$$Q = 189.91 \times 10^{12}$$

The poles of the analog band-pass filter transfer function were shown (graphically in Figure 3.5) to be:

$$-63.567 \pm 3.8421j \times 10^{3}$$

$$-58.188 \pm 3.5859j \times 10^{3}$$

The analog filter is therefore stable.

To transform the analog band-pass transfer function into a digital version we will use the Bilinear Transformation [Ref. 8: pp. 219-224] which is characterized by the following relation

$$s = \frac{2}{T} \frac{z - 1}{z + 1} \qquad\qquad 4.1$$

This transformation will map stable analog poles which are in the left-half of the s-plane into the interior of the unit circle in the z-plane. Thus stability is preserved in all cases.

If we then make the substitution $s = j\overline{\omega}$ and $z = e^{j\omega T}$ into Eq. 4.1 and simplify, we can establish the relationship between the frequencies in the analog and digital cases. (In this and the following discussion we shall denote frequencies in the analog case with an overbar ($\overline{\omega}$), and those in the digital case without one (ω).)

The resulting relation is

$$\overline{\omega} = \frac{2}{T} \tan \frac{\omega T}{2} \qquad\qquad 4.2$$

where T is the sample period given by $1/f_s$. In this case $f_s = (6.666 \times 10^6)/(4 \times 192)$, which we will show shortly. This results in $T = 1.15212 \times 10^{-4}$.

This relationship between analog and digital frequencies is shown in Figure 4.2 and reveals that the Bilinear Transform does not provide a linear mapping from one function to another. The frequency range from 0 to ∞ in the continuous case is warped into the frequency range from 0 to π/T in the digital case.

Therefore, if we have an analog filter with transfer function $\overline{H}(s)$, we may then perform the following substitution dictated by Eq. 4.1

$$H(z) = \overline{H}(s)\big|_{s=(2/T)[(z-1)/(z+1)]} \qquad 4.3$$

Another way of expressing this same relation is

$$H(e^{j\omega T}) = \overline{H}(j\overline{\omega})\,|\,\overline{\omega} = (2/T)\,\tan\,\omega T/2$$

Using this relation the characteristics of H(z) can be
obtained graphically from those of H(s) as shown in
Figure 4.2 [Ref. 5: p. 262].
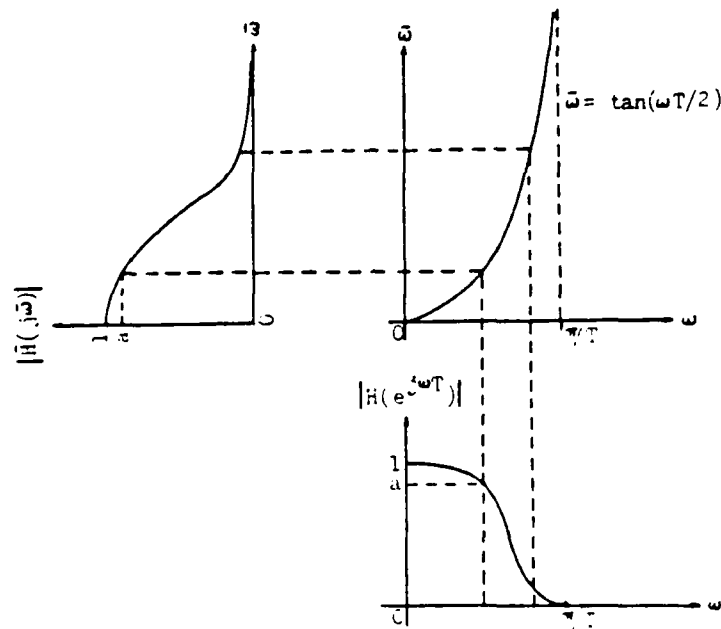
Figure 4.2   The Bilinear Transformation
(showing analog and digital transfer functions
and the non-linear warping of frequencies.)

We see from the figure that there is no aliasing problem
associated with the transform because the frequency is
limited to less than π/T (8680π) in the digital
case.   However, because of the frequency warping we have to
make a proper transform of frequency according to Eq. 4.2

before application of the Bilinear Transform. Consequently,
for a transformation of the analog band-pass filter derived
as Eq. 3.3, we must substitute $f_\bullet$ = 590.825 Hz for
$f_\bullet$ = 600 Hz before application of the Bilinear
Transform to ensure a proper transformation to the digital
domain. Once this is accomplished all we need do is apply
the Bilinear Transform to the resulting "pre-warped" analog
band-pass filter transfer function.

The FORTRAN based computer program previously introduced
in Appendix C also provides for this development and
implements Eqs. 4.2 and 4.3 to derive the following digital
transfer function $H(z^{-1})$ for the desired digital
band-pass filter

$$H(z^{-1}) = \frac{\rho(1 + Fz^{-1} + Gz^{-2} + Hz^{-3} + Jz^{-4})}{1 + Mz^{-1} + Nz^{-2} + Pz^{-3} + Qz^{-4}} \qquad 4.4$$

where the constants are as follows

ρ = 0.039516

F = -3.6279

G = 5.2861

H = -3.6279

J = 1.0000

M = -3.6251

N = 5.2586

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$P = -3.5768$

$Q = 0.97353$

The poles of the transfer function given by Eq. 4.4 are

$0.90781 \pm 0.40813j$ (Magnitude = .99533)

$0.90475 \pm 0.40493j$ (Magnitude = .99123)

POLE/ZERO PLOT FOR DIGITAL BPF
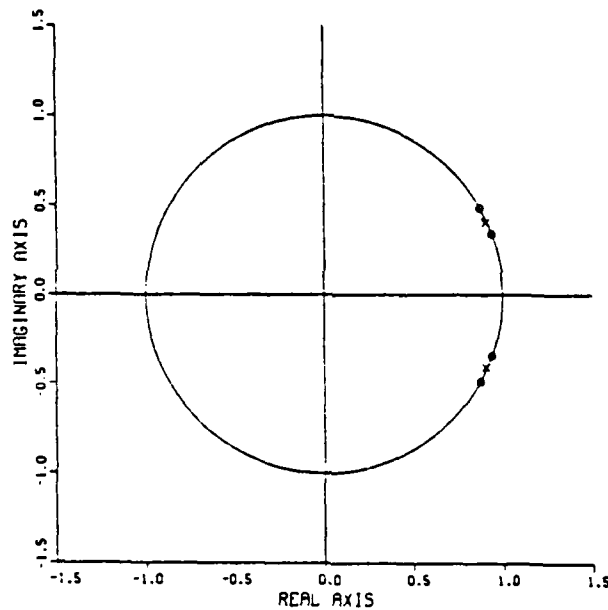
Figure 4.3 Pole/Zero Plot for the Digital Elliptic
Band-Pass Filter (poles appear singular, but are
in fact double and nearly coincident)

and thus we confirm the mapping of stable poles in the

analog domain into stable digital poles located inside the

unit circle. This digital pole/zero plot is shown graphically in Figure 4.3 on the previous page.

B. DIGITAL BAND-PASS FILTER SIMULATION

Equation 4.4 represents the digital filter transfer function equivalent to the analog filter transfer function we presented in Chapter 3. In a manner completely analogous to that development we are now able to demonstrate a computer graphical simulation of the digital filter frequency and phase response and compare these to the previous results. The FORTRAN program used to present this graphical output is included in Appendix E under the title DBPFR.

In Figure 4.4 we see the digital filter frequency response and observe that it is nearly identical to the analog response in consonance with our design goal. The minor differences are remarkable and explicable. The center frequency of the digital filter is diminished to the pre-warped center frequency of approximately 591 Hz. Additionally, the two peaks of the amplitude response located at about 585 Hz and 595 Hz are not of equal magnitude. This is due to the difference of pole proximity to the unit circle. Although the poles appear coincidental in the graphical presentation in Figure 4.3, they are actually distinct; the pole nearer to the real axis is some

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.004 units closer to the unit circle which accounts for the amplitude disparity between the two poles.

DIGITAL ELLIPTIC BPF FREQUENCY RESPONSE

NORMALIZED AMPLITUDE VS FREQ (FO-590 HZ)
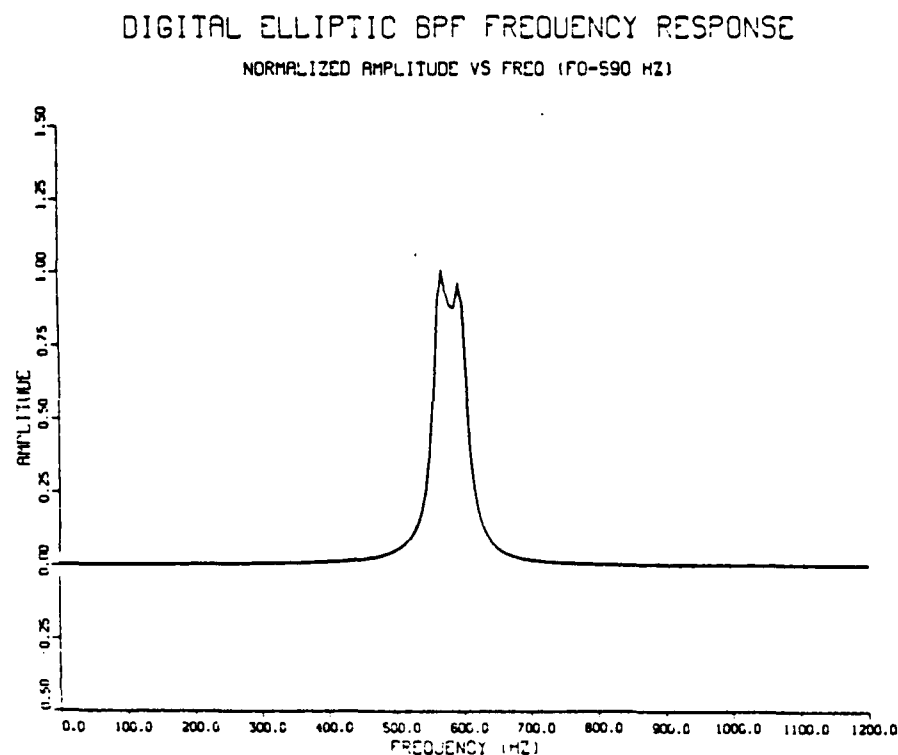
Figure 4.4   Digital Elliptic BPF Frequency Response
(Computer Simulated Amplitude Response)

In Figure 4.5 we observe the digital filter frequency response as measured in dB. This curve appears somewhat different from its analog counterpart but the important feature is maintained. A steep filter rolloff is realized out of the passband and the response is diminished by about 30 dB at approximately 500 Hz and 700 Hz according to design specifications. Although the analog filter did not deviate much from this 30 dB down figure we see an added benefit of

the digital filter wherein the rolloff continues

monotonically over our observed spectrum.

DIGITAL ELLIPTIC BPF FREQUENCY RESPONSE

AMPLITUDE (DB) VS FREQ (FO-590 HZ)
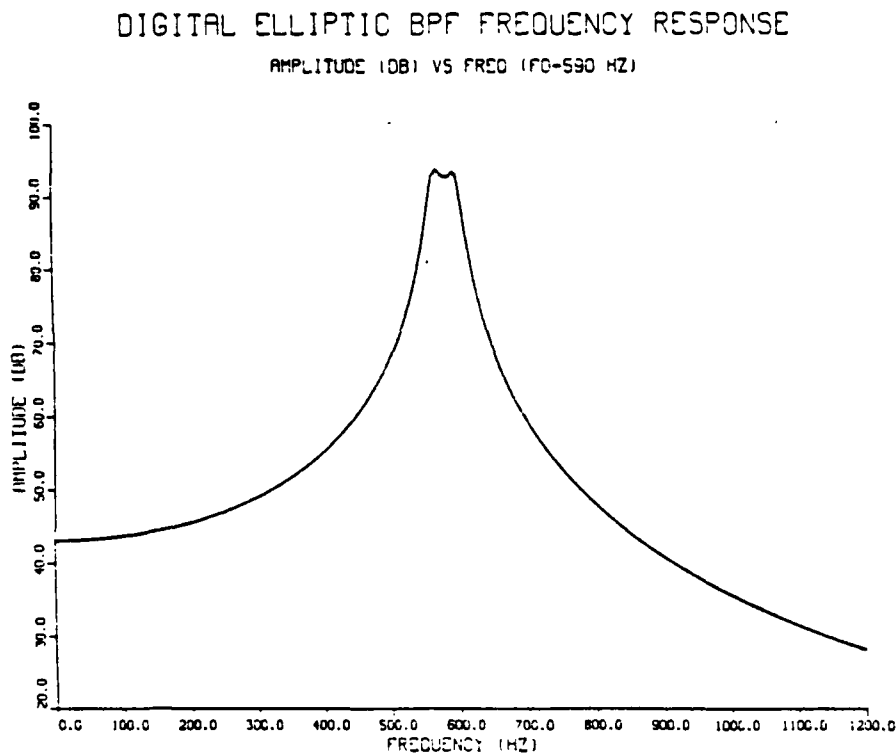
Figure 4.5   Digital Elliptic BPF Frequency Response
(Computer Simulated Amplitude Response in dB)

Finally, in Figure 4.6 we observe the phase response of

our digital filter.   Once again this closely approximates

the severe phase distortion we observed with the analog

filter although the center frequency is again confirmed to

be significantly less than the nominal 600 Hz we expected of

the earlier filter design.   To reiterate, this phase

distortion is a hallmark of elliptic filters and the

Bilinear transformation, but our application is not phase
dependent. Thus we may ignore this effect.

DIGITAL ELLIPTIC BPF PHASE RESPONSE

PHASE (DEGREES) VS FREQ (FO-590 HZ)
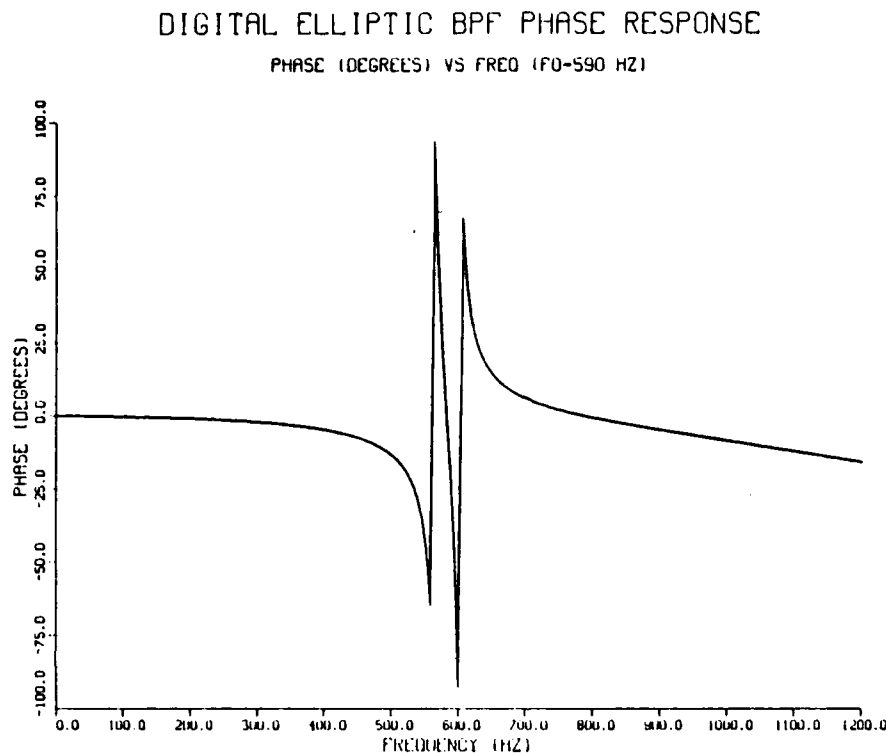
Figure 4.6   Digital Elliptic BPF Frequency Response
(Computer Simulated Phase Response)

C.   DIFFERENCE EQUATION REPRESENTATION

The transfer function for the fourth order Elliptic
Filter was given previously in Equation 4.4.   Section 4 of
the program ABPDBP introduced earlier in Appendix C
accomplishes a transformation of this quotient of fourth
order polynomials and provides an equivalent cascaded

representation of two second order filter stage blocks, each of the form

$$H(z) = \frac{Y(z)}{X(z)} = \frac{a_0 + a_1 z^{-1} + a_2 z^{-2}}{b_0 + b_1 z^{-1} + b_2 z^{-2}}$$

where $X(z)$ and $Y(z)$ refer to the filter input and output, respectively. The values of the dual quadratic coefficients of the cascaded second order transfer function and as computed by the program in Appendix 4 are given in Table 4.1.

Table 4.1

ELLIPTIC BPF SECOND ORDER STAGE COEFFICIENTS

1st Stage Coefficient	Value	2nd Stage Coefficient	Value
a_0	1.0000	a_0	1.0000
a_1	-1.7503	a_1	-1.8780
a_2	1.0017	a_2	0.9981
b_0	1.0000	b_0	1.0000
b_1	-1.8163	b_1	-1.8092
b_2	0.9910	b_2	0.9822

Both second order z-domain filter stage transfer functions can be manipulated in a familiar way to realize the following z-domain difference equation.

$$b_0Y(z) = a_0X(z) + a_1X(z)z^{-1} + a_2X(z)z^{-1}$$
$$- b_1Y(z)z^{-1} - b_2Y(z)z^{-1}$$

Applying the inverse z-transform to this z-domain difference equation yields the time domain digital difference equation .

$$b_0y(k) = a_0x(k) + a_1x(k-1) + a_2x(k-2)$$
$$- b_1y(k-1) - b_2y(k-2)$$

4.5

The Signal Flow Graph corresponding to the difference equation given by Eq. 4.5 is shown in Figure 4.7. The difference equation representation is important because this is the basis for the hardware implementation of the digital filter which shall follow in Chapter 5.
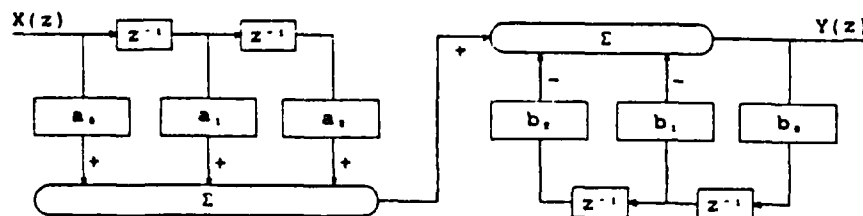
Figure 4.7   Second Order Stage Signal Flow Graph

D. DIFFERENCE EQUATION IMPLEMENTATION SIMULATION

We have just stated that the difference equation

representation of the digital filter will become the basis

for the INTEL 2920 Signal Processor implementation which is

to follow. In order to show the adequacy of this method of

implementation it is useful to demonstrate the impulse

response and filter frequency response by computer

simulation. In the following chapter sections we will

demonstrate these simulations and show that they yield

results in keeping with our design expectations.

1. Digital Filter Impulse Response

In Appendix F is presented the complementary FORTRAN

programs S22I and S22IG. Both implement the impulse

response simulation for the difference equation

representation of the digital elliptic band-pass filter. In

the case of S22I the output is digital and is shown to

exemplify the filter response over a greater period of time

than is usefully represented otherwise. In the case of

S22IG the output is graphical and will be presented here.

In both these programs the impulse is equal to the

greatest allowable input which guarantees an output of less

than unity. This is done for reasons of filter stability as

well as a limitation of the INTEL 2920 which will be

discussed in the next chapter. By examining the impulse

response we confirm the stability of the filter design by

ensuring that the output decays to zero over time. In

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addition we can observe the natural response of the system
by establishing the frequency of the decaying sinusoid.

DIGITAL FILTER IMPULSE RESPONSE
OUTPUT VS ITERATION
INPUT - .017 (SINMAG) AT T - 0
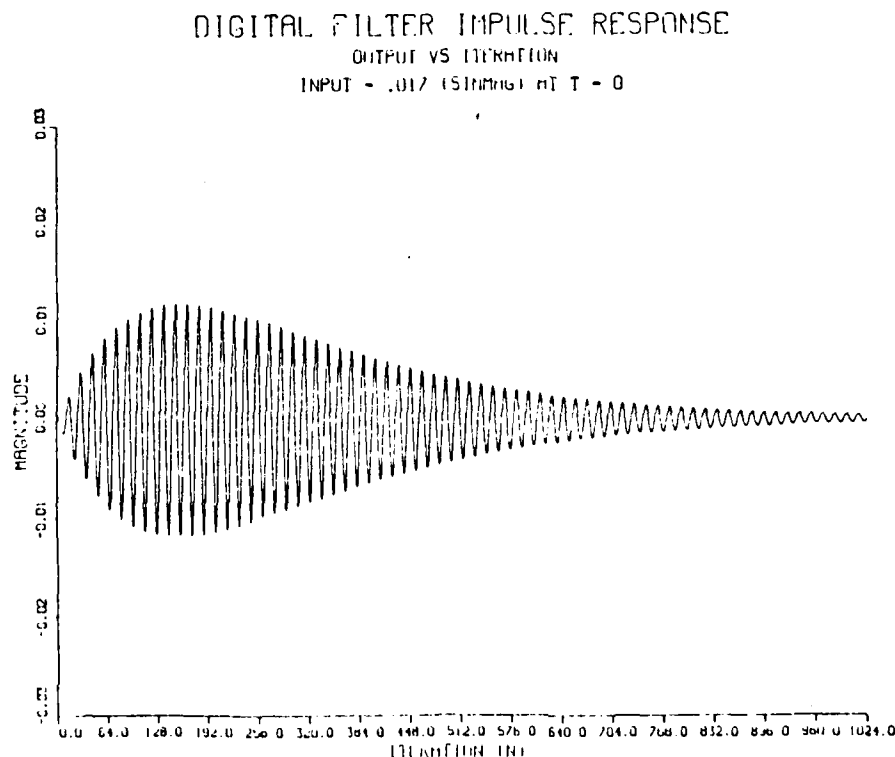
Figure 4.8   Digital Filter Impulse Response

In Figure 4.8 we observe the the response of the two
stage difference equation filter for an input of 0.0172
applied at time T = 0.   By counting the number of cycles
which occur over a corresponding number of iterations, and
realizing that the sample period is 0.11521 milliseconds we
arrive at natural frequency which is very close to the
expected 600 Hz.   Additionally, it is apparently true that
the response decays to zero with time, at least over the

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Although we have ensured an input less than one volt this is not sufficient to guarantee that the post-processing value will not exceed the internal arithmetic limit. Internal arithmetic is limited to a range of values which cannot exceed -1.00000000 to +0.99999999. These 8 decimal place accuracies are established by the internal 25 binary bits (1 sign bit and 24 magnitude bits) available for arithmetic computations within the 2920. Actually the range of multiplicative inputs is only good to within 4 decimal places due to the scaling problem. But this will be seen to be more than adequate for our purposes.

To ensure that the processed values do not exceed one volt we scale down the digitally sampled input value by 64 by way of program step 44. The difference equation manipulations of the input value are then accomplished in program steps 47 through 130.

Digital arithmetic is performed in the 2920 by means of binary shifting and adding which is predicated on a transformation of coefficients to a nearest binary equivalent. The FORTRAN program and its output which performs this transformation is labelled CTRANS2 and is shown in Appendix I. Although a binary transformation does involve some approximation error, we see in the appendix that the worst case approximation of coefficients is still within .02 percent of the actual value. This is a relatively insignificant error.

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D. A 2920 DIGITAL FILTER IMPLEMENTATION

Here we shall describe the particular 2920 software and hardware components which comprise the digital filter.

1. 2920 Assembly Language Program

In Appendix H we find the 2920 assembly language program which implements the two stage difference equation developed in Chapter 4. Recognizing the characteristics of the 2920 processor, it is instructive to review the programming devices which are brought to bear to realize this filter. We will proceed in the order in which these devices are used in the program. Appendix H should be consulted as reference for the discussion which follows. A detailed discussion of the 2920 Assembly Language should be consulted for particulars concerning the language [Ref. 11].

After initializing the DAR register we accept the input analog sample from the sensor microphone/preamplifier ensuring that the level does not exceed 1.0 volts. This limit is established by the voltage reference circuitry at pin #8 of the 2920. The input analog value is stored in the Sample/Hold register.

We then begin a sequence of steps, according to 2920 protocol, which accomplish the analog to digital transformation of the input value in the Sample/Hold register. This procedure is completed at program step 43 and the resulting digital value is then found in the DAR register.
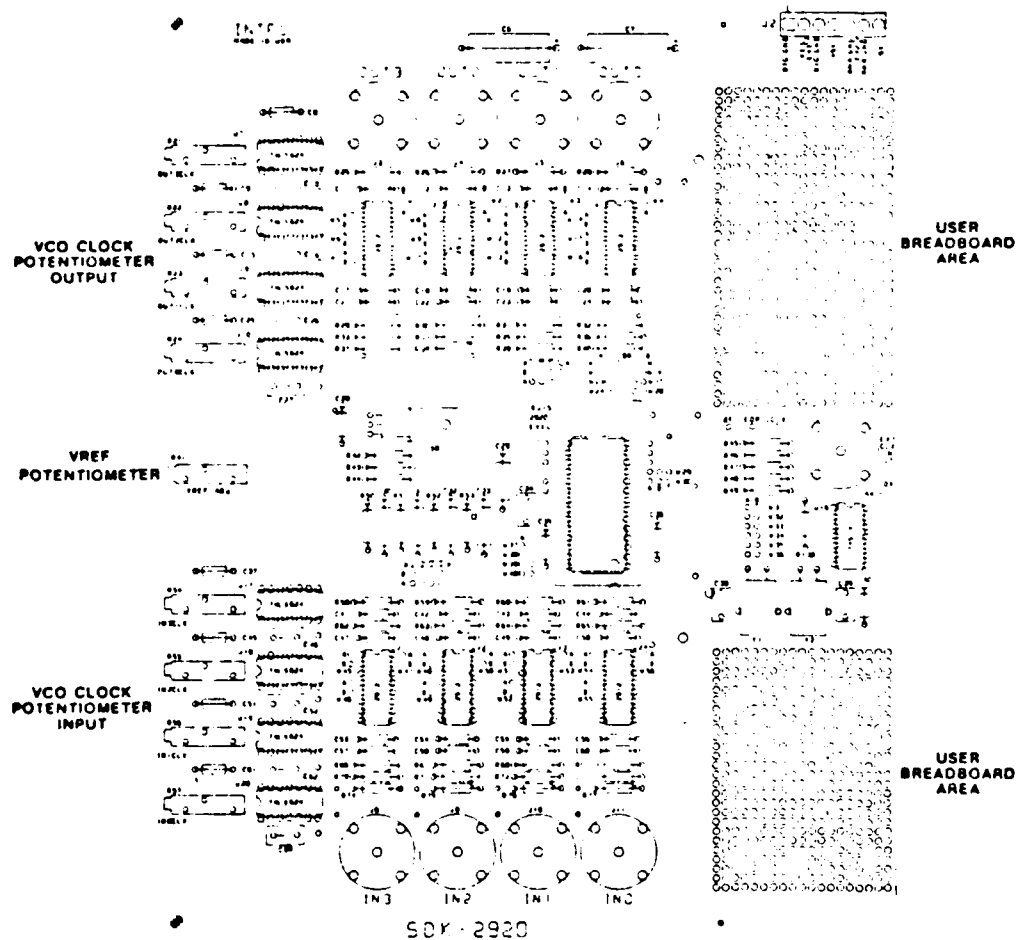
Figure 5.3   SDK-2920 Applications Board
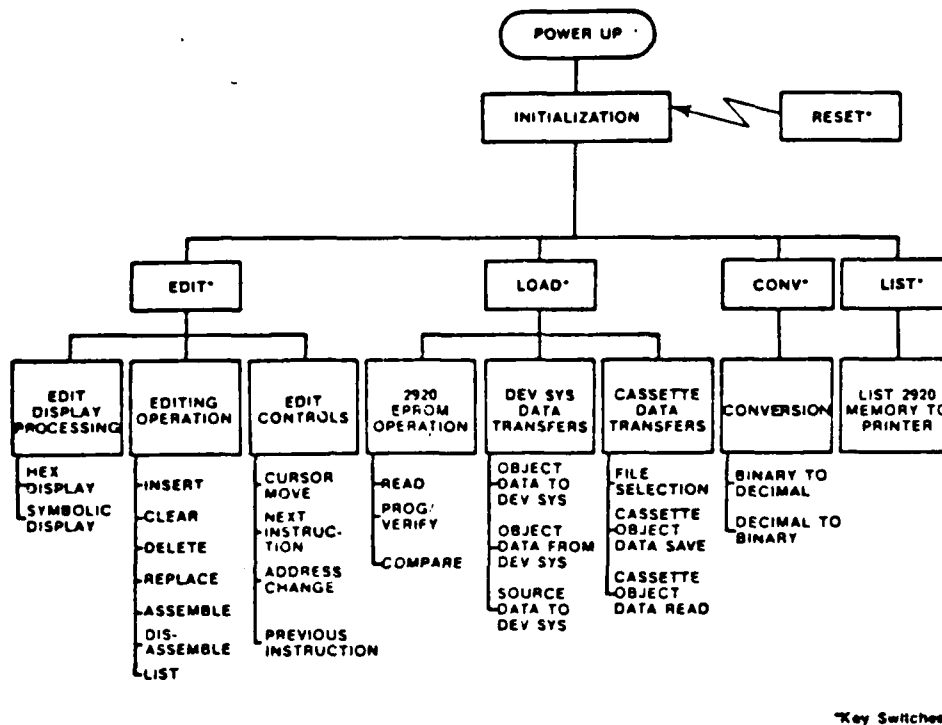
Figure 5.2 SDK-2920 Monitor Command Structure

of the SDK-2920 by examination of inputs and outputs. The

applications board is shown in Figure 5.3 on the page

following. Provisions are made on the board for assembly of

either internal or external clocks, four input and four

output channels with associated waveshaping circuitry,

reference voltage development, and two user breadboard areas

for specific applications development. Furthermore, TTL

compatible output signals can be delivered to the output

vice analog outputs if desired. We shall make use of this

feature to send a signal detection pulse when the APU

ignition is detected.

Applications software was developed using an Intellec Microcomputer Development System running a 2920 Assembly Program and Software Simulator. Transfer of 2920 software between the development system and the SDK-2920 is easily accomplished.

The SDK-2920 is physically divided into a development side and an applications side. The development side can be used to load, test and modify EPROM resident programs under 8085A microprocessor control. System control is accomplished with the use of a keypad monitor. The composition and hierarchy of the monitor command structure is shown in Figure 5.2 on the following page.

The applications side includes a prototype area for circuit construction and testing. It functions independently of the development side. After program development has taken place two methods may be used to accomplish program verification. The first method uses the Intel SM2920 Simulator Software to simulate the execution of programs written for the 2920. This simulator allows the use of symbolic references for changing and displaying all 2920 registers, flags and user-defined locations in program and memory storage. A trace feature also allows monitoring of selected parameters as they are changed under program control.

The second method of 2920 program verification is done by monitoring circuit performance on the applications side

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these functions the analog section includes the following subsections:

-- a four input multiplexer

-- an input sample-and-hold circuit

-- a D/A converter

-- a comparator

-- an output multiplexer with eight output sample-and-hold and buffer amplifiers.

.-- a special digital-to-analog (DAR) register which acts as an interface between the digital and analog sections.

C.   THE SDK-2920 DEVELOPMENT SYSTEM

The SDK-2920 Development System is an integral component in the development of any applications package which uses at its core the INTEL 2920 Analog Signal Processor [Ref. 10]. Within the scope of the system are many development capabilities including

-- Breadboarding: The breadboard is used to develop circuits for evaluation or prototype applications.

-- Assembling and Editing: This feature is comprised of an assembler, disassembler, hexadecimal display, symbolic 2920 instruction display, and single keystroke entry of many 2920 instruction fields.

-- 2920 EPROM Programming: The development board includes hardware and control elements necessary to program the 2920.

-- Communications: The development also interfaces with Intel Developments Systems (such as the Intellec Series) to pass object and source code listings of 2920 programs.

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function, any applications program cannot make use of more than 192 instructions to process whatever number of input and output signals are being manipulated. But despite this restriction the power of the 2920 is evident. In our application we will only make use of a single input/output channel.

B. 2920 FUNCTIONAL DESCRIPTION

. Figure 5.1 on the previous page details the block configuration of the 2920 [Ref. 9]. It is divided into the three major subsections described as follows.

The 192 x 24-bit Program Memory Section is a storage area implemented with EPROM. This section includes the instruction clock and timing circuits and program counter which control the operation of the entire device, including the other two sections.

The Arithmetic Section includes a 40 word by 25-bit scratchpad RAM and an arithmetic and logic unit (ALU). Both the RAM and the ALU are two port access devices. In the case of the ALU one of the ports is passed through a barrel shifter scaler. The function of the arithmetic section of the 2920 is to execute the commands dictated by the program memory.

The Analog Section performs A/D and D/A functions upon command from the program memory. In order to implement

In addition to the precision and speed of computation which the 2920 offers, it also allows for sequential processing of up to four separate input signals and eight analog output signals in a single program pass. This is of course dependent upon program complexity--regardless of
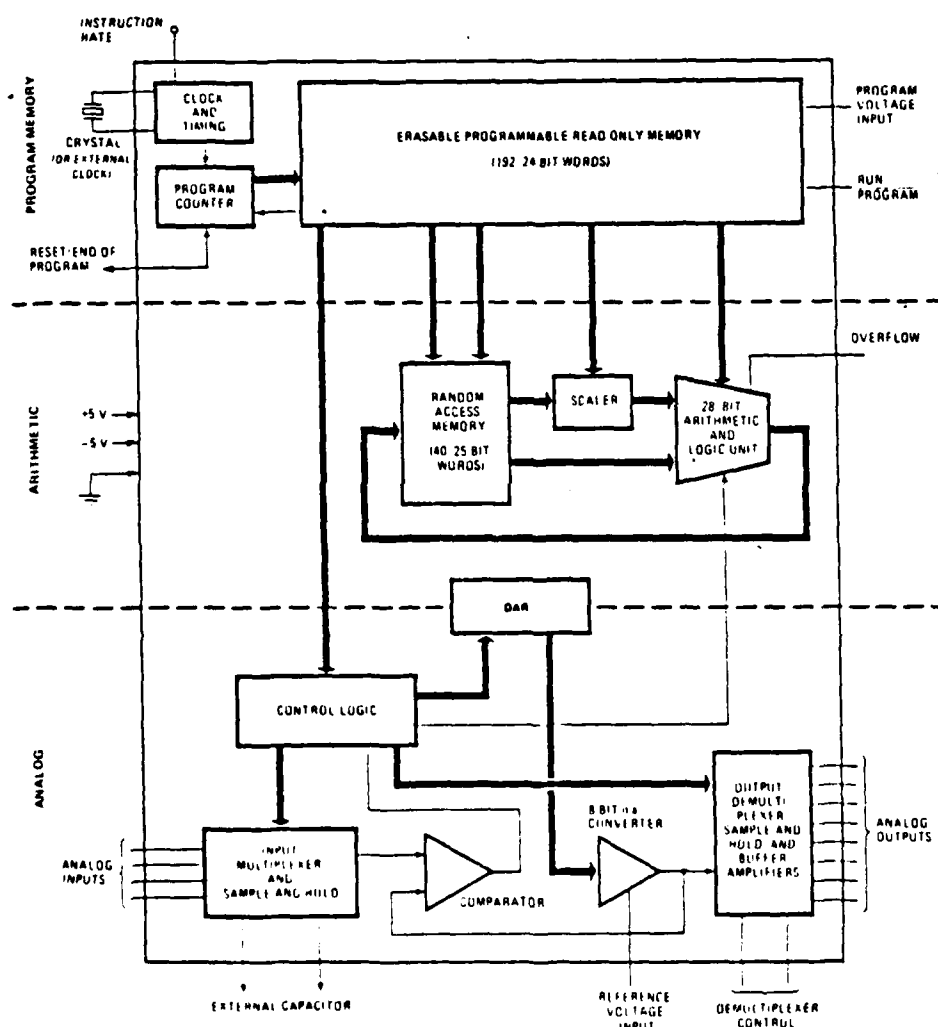
Figure 5.1   2920 Functional Block Diagram

Several logical conditions are allowed which affect program manipulation of data, but none will cause the processor to execute a program step out of sequence. In fact the only effective jump is performed at the last instruction which provides for a return to the beginning of the program loop. In this way the programmer may provide for an exact digital sample interval based upon program loop execution time. The shorter the program implementation loop the greater is the processor capacity to provide a faster sampling frequency.

The necessity of providing for an accurate sampling interval arises out of an understanding of the characteristics of the sampled analog signal being processed. Without an accurate clock interval, provided for in the 2920 by the program execution loop time, significant noise can be introduced in the system. Even small variations in the sampling interval can render the analysis useless through the introduction of intolerable measurement noise.

Each 2920 program instruction requires four clock cycles to execute. Given our nominal 6.666 MHz clock (the maximum allowed) the 2920 can therefore realize a maximum sampling frequency of 8.680 kHz over a 192 instruction program loop. This allows for a device bandwidth of greater than 4 kHz. Shorter programs naturally allow for a greater sampling frequency and thus higher device bandwidth.

V. THE INTEL 2920 ANALOG SIGNAL PROCESSOR

A. OVERVIEW

The INTEL 2920 Analog Signal Processor is actually a digital processor which is implemented to perform analog signal processing functions. Introduced in 1979, the 2920 system is centered about the 2920 single-chip microcomputer which is specially designed to process real-time analog signals. This single chip includes within its 28-pin DIP configuration sufficient hardware to provide 192 program memory locations, scratchpad memory, digital to analog (D/A) circuitry for up to four separate sampled inputs, analog to digital (A/D) capabilities for eight individual outputs, a digital pipeline processor capable of up to twenty-five bit accuracy, and input/output (I/O) control circuitry [Ref. 7: p. 3-1 through 3-2] . The 2920 is capable of implementing a wide variety of functions which rely upon sampled digital data techniques. We will use the 2920 to implement our matched filter design which will detect the APU start.

At the heart of the 2920's significant power is its on-board erasable programmable read-only memory (EPROM) which allows the user the convenience of customizing the 2920 for each intended application. Because the 2920 is a pipeline processor all program steps are performed sequentially without any conditions which may impact upon execution time.

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filter. We shall see in the discussion which follows that the sampling frequency will be 8680 Hz. Thus our band of input frequencies is limited to less than one-half of this value, or 4340 Hz. Because our frequency of interest is 600 Hz we have considerable freedom in choosing the cut-off frequency of our anti-aliasing filter.

One option available to us is to design a low-pass filter with a rolloff which meets our needs. However, there are such filters commercially available which implement a compatible response which minimizes the effort required of the designer. One such filter is the INTEL 2912A which has been specifically included in the hardware kit we shall use to implement the digital filter we have just developed. This hardware implementation is the subject of Chapter 5.

output at 600 Hz is significantly less than at 590 Hz and even 575 Hz. This is indicative of both a steeper filter rolloff at frequencies greater than the center frequency and the effect of coefficient approximation which will be discussed more fully in the next chapter. The frequency response at both 500 Hz and 700 Hz is expectedly minimal but may not be usably low. If we find that the filter rolloff is not great enough and the response out of the passband is too great for our purposes then further design modifications may be undertaken. Accordingly, we could increase the order of our filter design. This would increase the number of filter stages in the analog implementation and therefore the complexity of that design. But, as we shall see, to a certain extent this additional filter complexity in the difference equation may be absorbed by the digital implementation we shall pursue without any increase in the hardware. These considerations will have to be examined more completely in the final analysis of the filter design effectiveness.

E. ANTI-ALIASING FILTER

When implementing a digital filter it is necessary to employ an analog input anti-aliasing filter to limit the band of input frequencies to less than half of the Nyquist sampling rate. This corresponds to the need to implement a low-pass filter at the input to the digital band-pass

data to recreate the frequency response. This is shown in Figure 4.9. The figure confirms a narrow band-pass filter function with a center frequency at approximately 585 Hz. This is very close to the design center frequency of 591 Hz and is, in fact, within the error of a single bar in this pattern representation.

2. Digital Filter Frequency Response

Now that we have confirmed the stability of our filter design we can proceed to examine the frequency response of the filter over the range of interest. In particular we shall examine the filter frequency response over several frequencies in the range of 500 Hz to 700 Hz. The FORTRAN programs which allow this examination are S22F and S22FG which are included as Appendix G to this thesis. Due to the number of output figures they will be left in the appendix and we shall only give a summary of their content.

The digital filter frequency response was examined for the following frequencies: 500, 575, 590.825, 600, 625 and 700 Hz. The 590.825 simulation was chosen because this is the design center frequency (due to pre-warping) and we wish to confirm an output maximum amplitude at this frequency. From the figures in the appendix it is easy to see that the filter does in fact yield the response we desire. The maximum output amplitude does occur for the expected frequency, although the output at 575 Hz does not diminish appreciably from this value. However, we observe

approximately one-tenth of a second represented by the
duration of the overall sample period in the figure. To
confirm this suspicion we can carry out the impulse response
for a substantially longer period of time, say over one full
second, or approximately 8192 iterations. The results of
this computation are shown in the output of S22I in the
appendix. They confirm the occurence of the maximum
amplitude of impulse response output at the xxxth iteration
which is what we observe in the figure.

Having realized the digital filter impulse response
output we can perform a discrete Fourier transform of this

DFT OF DIGITAL FILTER IMPULSE RESPONSE

MAGNITUDE VS FREQUENCY
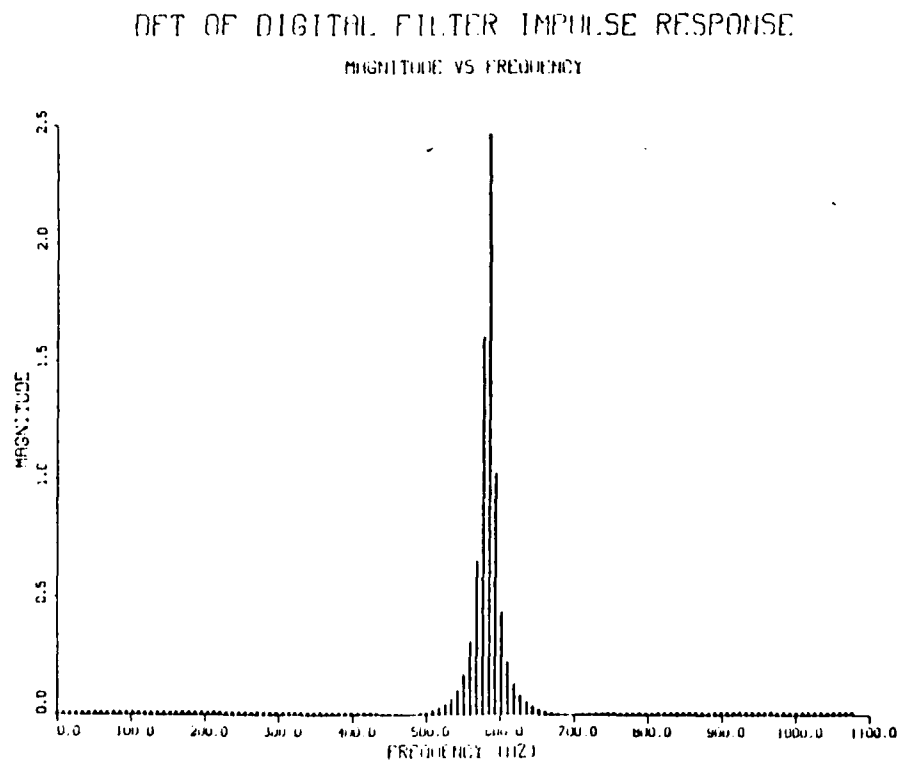
Figure 4.9 Discrete Fourier Transform of
the Digital Filter Impulse Response

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After the difference equation implementation in each
program pass we are left with a binary value in the DAR
register which corresponds to the program output for that
pass. We have the option of providing a certain amount of
linear output gain by an appropriate shift of the output
binary value now in the DAR. In program step 132 we provide
a gain of four by a left shift of two binary positions. We
output this value to channel 0 in steps 139 through 142.

The final program manipulation occurs in program
steps 143 to 150. Here we perform a serial register shift
of present program pass values in preparation for the next
program pass. Program step 191 is the final executable
statement which returns us to step 0 for the next pass. The
entirety of the 2920 operation consists of an endless loop
of these instructions.

2. **2920 Hardware Implementation**

The 2920 contains an EPROM which is loaded with the
hexadecimal code which is equivalent to the assembly
language program just described. However, there are several
other component devices which are integral to the operation
of the 2920. The relation of these devices to the 2920 will
now be described. A graphical schematic of these components
appears in Figure 5.4.

At the input side of the 2920 an anti-aliasing
filter is realized by using a 2912A which actually contains
two filters which are cascaded together. This configuration
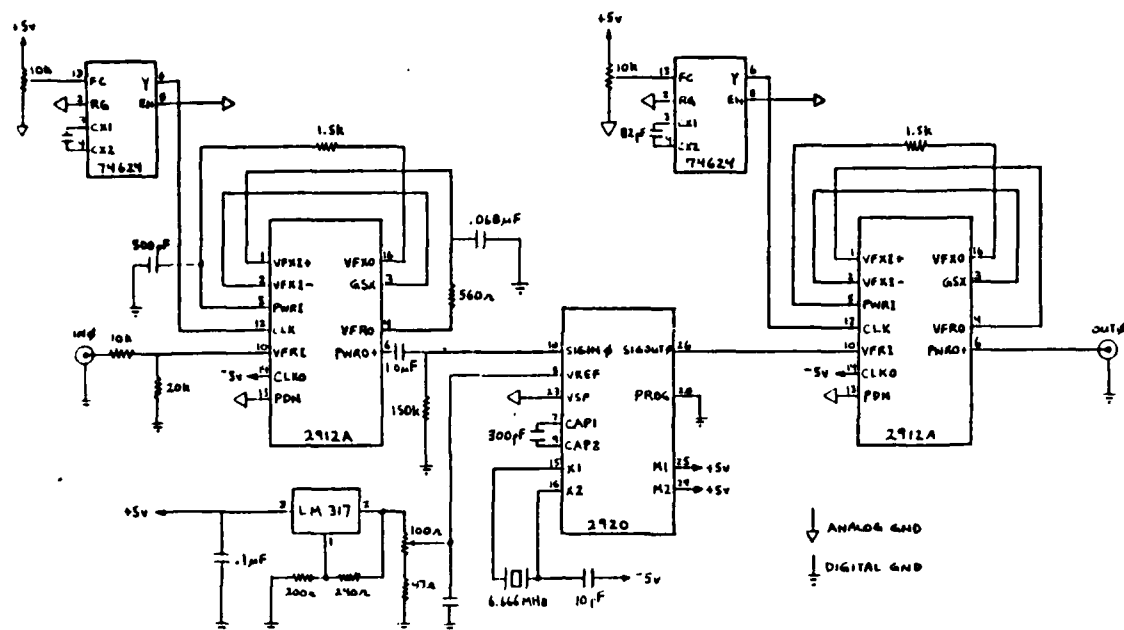
Figure 5.4   2920 Digital Filter Schematic

provides 54 dB of input dynamic range and a nearly flat

response for frequencies less than 3 kHz.   There a steep

roll-off commences and at about 4 kHz the cascaded filter

combination provides over 30 dB of attenuation.   This

supports the Nyquist frequency limit which is 4.34 kHz in

this application.

The 2912A is a pulse code modulated filter which

requires a clocking input to realize its filter function.

This is provided by the 74624 at its input.

At the output of the 2920 another 2912A is employed

in identical configuration and now provides a reconstruction

filter for our application.   This filter smooths the output

of the 2920 to provide an analog signal for follow-on logic

discrimination as shown earlier in Chapter 3.

A 2920 option which is not demonstrated here yet

will be employed in final filter configuration is to obviate

the need for external signal conditioning by allowing

program discrimination of the output value and thus

providing a processed TTL signal output. This eliminates

the need for the external circuitry shown in Figure 3.8 and

therefore represents one significant advantage of the 2920

digital design over the analog implementation.

E.   2920 DIGITAL FILTER IMPLEMENTATION RESULTS

We will now proceed to demonstrate the results of the

2920 digital filter implementation in much the same manner

as the presentation which accompanied the analog filter

design in Chapter 3. We begin with a photograph of the

digital filter frequency response to a ramped sinusoidal

input. This is shown in Figure 5.5. The same method was

used to generate the sweep oscillation although the range of

sweep is not identical to that employed in generating

Figure 3.9. The result is that we cannot guarantee the

narrow bandwidth of this digital filter relative to its

analog counterpart by this means alone. The intent is, as

before, only to demonstrate that a narrow band-pass filter

response is generated.
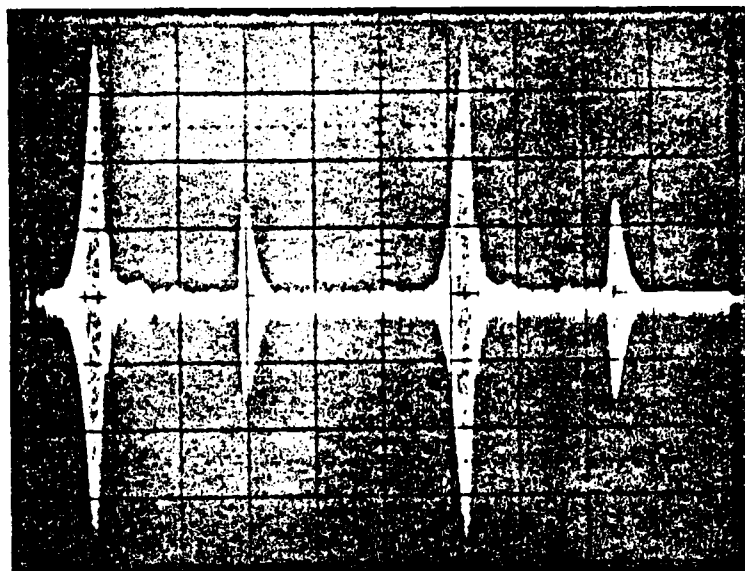
Figure 5.5   Digital Elliptic BPF Frequency Response
(Photograph of Actual Filter Amplitude Response
to a Ramped Sinusoidal Input)

To confirm the operation at the desired band-pass center

frequency we next apply discrete sinusoidal inputs to the

digital filter at various frequencies arrayed about 600 Hz.

The result is the digital analog to Figure 3.10 which is

shown here as Figure 5.6.   The scale is maintained as in

Figure 3.10.   The input frequencies are at about double the

amplitude of the analog filter to ensure proper operation.

This implies that despite the relative immunity of the

digital filter to input amplitude variations we must

nontheless provide an input above approximately 100

millivolts peak-to-peak.   However, once above this threshold
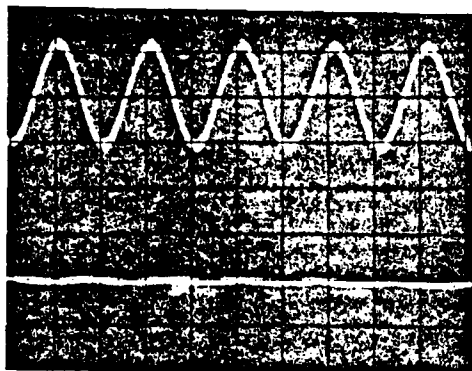
a) 500 Hz   b) 575 Hz
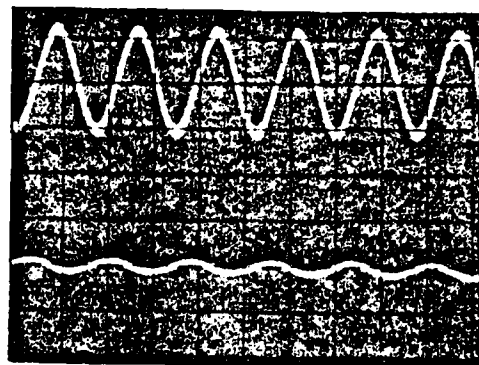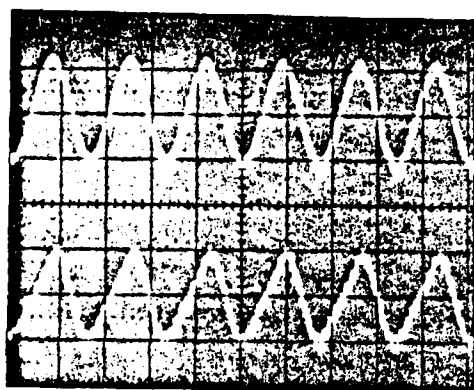
c) 600 Hz
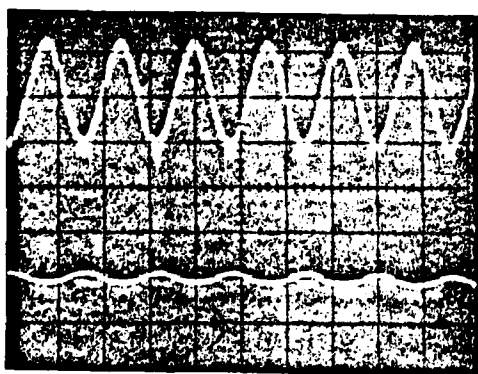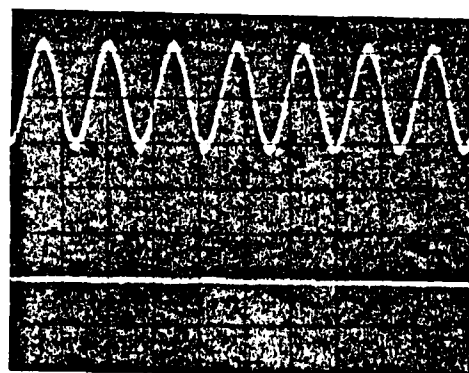
a) 625 Hz   b) 700 Hz

Figure 5.6 Digital Elliptic BPF Frequency Response
       Upper trace (Input):   50 mV/div scale
       Lower trace (Output):   1.0 V/div scale

value the digital filter provided a relatively undistorted and largely constant amplitude output up to an input amplitude of over 5 volts peak-to-peak (and this despite the 1 volt reference level of the input). Figure 5.6 thus confirms the center frequency maximum at a value near 600 Hz and a steep roll-off on either side of this value.

VI.   ALTERNATIVE FILTER CONCEPTS

The preceding development was based upon techniques used in implementing an Infinite Impulse Response (IIR) digital filter. Simply stated, an IIR filter realizes its output based upon the values of all present and previous inputs and outputs. In other words, feedback is employed in an IIR design.

In the general case, an IIR filter will have M finite zeroes and N finite poles. The zeroes of H(z) can be anywhere in the z-plane but the poles must lie within the unit circle to guarantee stability. In the case we have developed, a digital filter realization derived from an analog design, the order of M must be less than or equal to N. This describes an Nth order digital filter.

The hardware implementation of an IIR design usually involves the cascading of elemental single pole filters with double complex pole filters. These elements are derived from the original transfer function using a partial fraction expansion separation scheme.

There are other methods for realizing the filter we desire other than the a priori scheme we have developed so far. These generally use the input signal itself as a basis for the filter transfer function coefficients and involve an

adaptive evaluation of the proper coefficients which yield

the desired filter response.

A. A WIENER FILTER DESIGN--THE ADAPTIVE LINEAR COMBINER

The Adaptive Linear Combiner (ALC), shown in Figure 6.1,

forms the basis for the Adaptive Filter design we shall now

discuss [Ref. 12]. An input analog signal may be digitally

sampled in accordance with the Nyquist criterion and we may

then apply N sequential elements of that sample block to
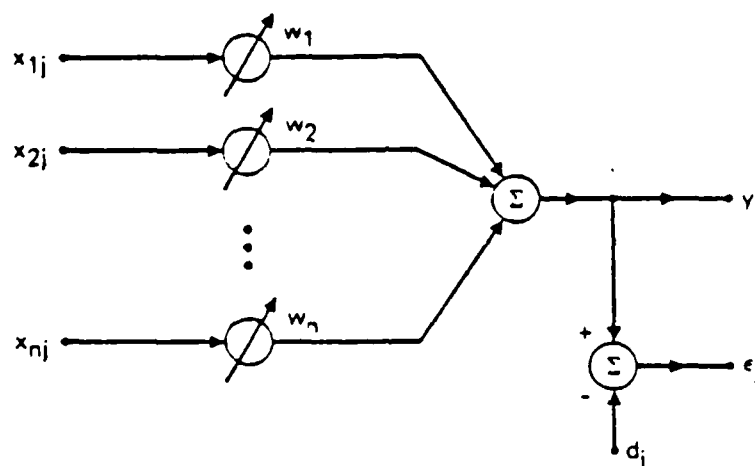
Figure 6.1   The Adaptive Linear Combiner

the ALC inputs. These inputs can be easily derived from a

tapped delay line which cascades sample values along in

sequential storage for processing. This scheme lends itself

well to implementation in a processor such as the 2920 which

is designed to accept sequential values by way of its

component A/D converter and RAM storage.

The set of measurements x_{nj} is multiplied by a corresponding weighting term W_i, and the results then summed to yield the output y_j. This output is then compared to a desired signal value for that instant and the difference between them constitutes an error signal ϵ_j. The objective of the ALC is to determine W_i so as to minimize ϵ_j for each set of sampled inputs and thus realize the weighted sum of input signals that best matches the desired response.

1. Theoretical Foundations

At the nth instant of time the output of the Non-Recursive Wiener ALC, $y(n)$, is given by [Ref. 13]:

$$y(n) = \sum_{j=0}^{N} x(n-j)W_j$$

$$= W_0 x(n) + W_1 x(n-1) + \ldots + W_N x(n-N)$$

which may be written in matrix form as

$$= \underline{W}^T \underline{X}$$

or equivalently

$$= \underline{X}^T \underline{W}$$

where T represents the matrix transpose operator, the set of N+1 weights is denoted by

$$\underline{W}^T = [W_0 \ W_1 \ \ldots \ W_N]$$

and the set of present and N previous inputs is given by

$$\underline{X}^T = [x(n) \ x(n-1) \ \ldots \ x(n-N)]$$

The error signal e(n) for time n is given by

$$e(n) = d(n) - y(n)$$

$$= d(n) - \underline{W}^T\underline{X}$$

and the square of the error (using the latter matrix notation) by

$$e^2(n) = e(n) \cdot e^T(n)$$

$$= [d(n) - \underline{W}^T\underline{X}][d(n) - \underline{X}^T\underline{W}]$$

$$= d^2(n) - 2d(n)\underline{X}^T\underline{W} + \underline{W}^T\underline{X}\underline{X}^T\underline{W}$$

The mean square error, obtained by taking the expected value of this last equation, is given by [Ref. 13]

$$E[e^2(n)] = E[d^2(n)] - 2E[d(n)\underline{X}^T]\underline{W} + \underline{W}^TE[\underline{X}\underline{X}^T]\underline{W}$$

Defining the vector Φ_{xd} as the cross-correlation between d(n) and $\underline{X}$ then yields

$$\Phi_{xd} \equiv E[d(n)\underline{X}]$$

$$= E[d(n)x(n), d(n)x(n-1), \ldots, d(n)x(n-N)]^T$$

The input auto-correlation matrix Φ_{xx} is defined as

$$\Phi_{xx} = E[\underline{XX}^T]$$

which may be written in expanded notation as

$$= \begin{bmatrix} x(n) \\ x(n-1) \\ x(n-2) \\ \cdot \\ \cdot \\ \cdot \\ x(n-N) \end{bmatrix} [x(n) \ x(n-1) \ \ldots \ x(n-N)]$$

Now if we carry out the indicated vector multiplication we arrive at the following result [Ref. 13]

$$= \begin{bmatrix} x(n)x(n) & x(n)x(n-1) & \ldots \\ x(n-1)x(n) & x(n-1)x(n-1) & \ldots \\ \cdot & \cdot & \\ \cdot & \cdot & \\ \cdot & \cdot & \\ & & x(n-1)x(n-1) \end{bmatrix}$$

And thus we arrive at the following form of the input correlation matrix

$$= \begin{bmatrix} \varphi_{xx}(0) & \varphi_{xx}(-1) & \cdots & \varphi_{xx}(-N) \\ \varphi_{xx}(1) & \varphi_{xx}(0) & \cdots & \varphi_{xx}(1-N) \\ \vdots & \vdots & & \vdots \\ \varphi_{xx}(N-1)\varphi_{xx}(-N) & \cdots & \varphi_{xx}(-1) \\ \varphi_{xx}(N) & \varphi_{xx}(N-1) & \cdots & \varphi_{xx}(0) \end{bmatrix}$$

In order to find the optimal weight vector, $\underline{W}^*$, we can differentiate the mean square error function with respect to the weight vector $\underline{W}$ to yield

$$\frac{d(e^2(n))}{d\underline{W}} = -2[\Phi_{xd} - \Phi_{xx}\underline{W}]$$

The optimal weight vector , $\underline{W}^*$, generally called the Wiener weight vector, is obtained by setting the quantity in brackets equal to zero. This results in

$$\underline{W}^* = \Phi_{xx}^{-1}\Phi_{xd}$$

The objective of processes involving the ALC is to find a solution to this equation. In fact we may employ an adaptive algorithm which uses the error signal, $\epsilon(n)$, (generated for each instance of filter inputs), as the basis

for modifying the filter weights until a minimum error is
attained for a particular input block. This describes the
Adaptive Transversal Filter shown in Figure 6.2 [Ref. 12].
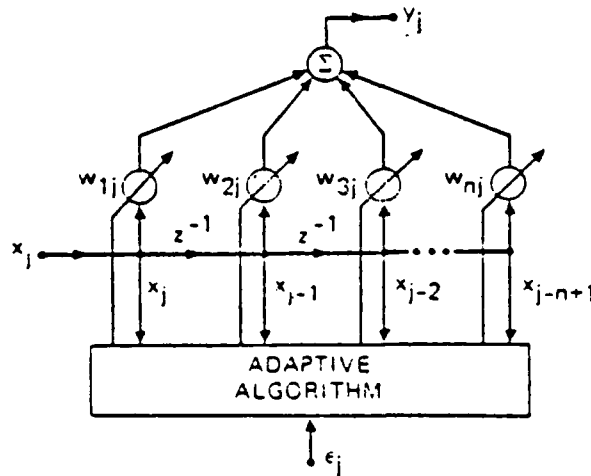
Figure 6.2   The Adaptive Transversal Filter

The Adaptive Transversal Filter (ATF) is a Finite
Impulse Response (FIR) filter owing to the lack of direct
feedback from output to input. If we employ a tapped delay
line at the input to the ALC which comprises the ATF the
form of the input vector becomes a finite number of delayed
elements of the input signal. It is therefore easy to see
that the impulse response of the ATF is just the sequence
corresponding to the elements of the weight vector, $\underline{W}$.
Such a filter can have any impulse response of length less
than or equal to its own length. Allowing for an ideal
unlimited length we could realize any impulse response at

94

all, and thus any frequency response. Practically, however, we are limited by filter complexity, error due to misadjustment, and an adaptive time constant which corresponds to filter length.

Thus we have a means of generating the desired filter response by applying the very signal we wish to detect. If we apply a digital series of samples taken from an analog reference signal we can realize the filter weights which will provide our desired signal output stream at a later time.

Thus the idea is to sample the analog recording of the APU noise in the cargo bay prior to launch and to apply that input series of data elements to an ATF to realize the filter weights. We may then build a 2920 circuit which uses these weights as filter coefficients to provide our filter response.

2. A Software Simulation

As an example of this methodology we will now present an elementary simulation which was performed for an input which consisted of an equal amplitude application of the three fundamental frequencies of interest: 600 Hz, 1200 Hz and 1800 Hz. We chose to simulate an Adaptive Transversal Filter of fourth order which therefore consists of four weights.

One example of a software implementation which is designed to arrive at the four desired filter weights is
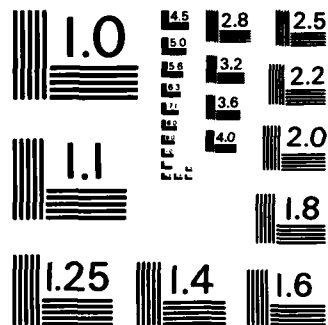
MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS – 1963 – A

shown in Appendix J as FORTRAN program FIR4. In this program we begin with trial weights and a range of upper and lower bounds. By repeated application of a library coefficient optimization routine (BOXPLX--also included in the appendix) we arrive at a set of four optimal weights within the bounds specified.

The result of this simulation is revealed through application of the FORTRAN program FIR4SIM which is included as Appendix K to this thesis. This result is shown in Figure 6.3. The input analog signal (indicated by the solid line) is a portion of the combined signal corresponding to
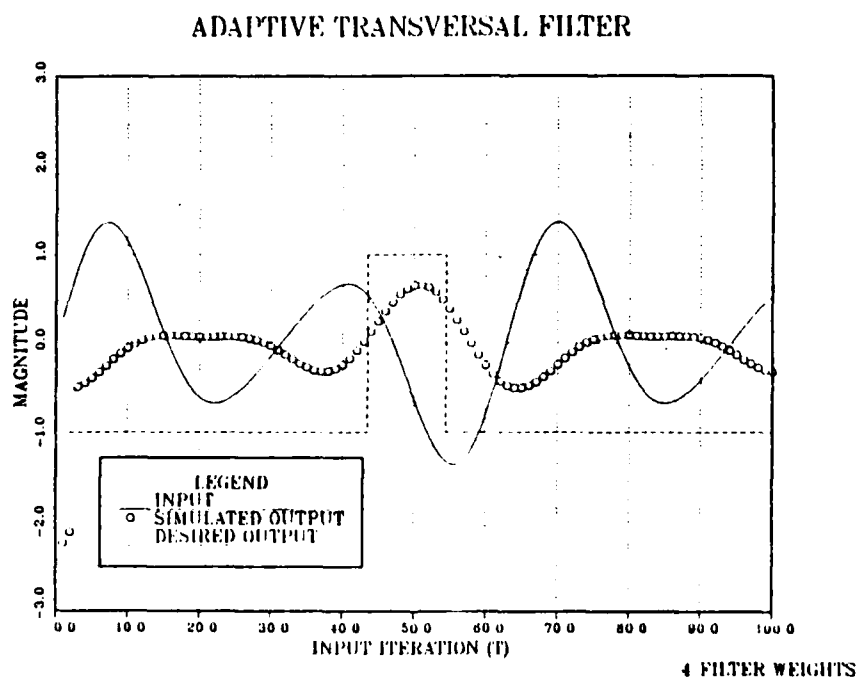
Figure 6.3 An Adaptive Transversal Filter Simulation

96

the three fundamental frequencies mentioned previously. The desired output (shown by the dashed line) is chosen to be a continuous -1 unless the signal of interest is detected. In that case the desired output jumps to +1.

As indicated in Figure 6.2 the Adaptive Algorithm samples the input signal and uses the successive present and three previous samples to arrive at the desired filter weights which will accomplish the task of signal discrimination. In the algorithm implemented by FIR4 of Appendix J we arrived at the following filter weights.

$$w_1 = -7.5060358$$
$$w_2 = 7.5403662$$
$$w_3 = 4.7097464$$
$$w_4 = -5.3987589$$

In Figure 6.3 we see that over 100 sample output iterations these weights resulted in an output which was at or near zero or below with a significant rise above 0.5 near the desired region. This approximates the filter response which would allow a useful discrimination of the desired signal by detection above a threshold floor (say 0.5 in this example).

This is by no means intended to be an exhaustive discussion of tnis approach to a matched filter design, but merely a consideration of an alternative approach which might be taken to realize a useful filter.

B. AN ANALOG SPEECH PROCESSING SCHEME

A further alternative which may be considered involves the use of commercially available speech processing microcircuits which often use Linear Predictive Coding schemes as the basis for their discriminant filters.

The current state of the art in speech recognition technology does not permit even the most sophisticated (and large) devices to recognize but several hundred words of vocabulary. The breakthroughs are most often in the arena of overcoming the speaker dependent nature of the simpler systems. However, all systems, be they single chip processors or multi-cabinet devices, do have the capability to analyze an audio input signal (conventionally this is speech of course) and to characterize the nature of changes in the formant composition over time.

Because the signal we wish to identify is in the audio spectrum it seems a logical idea to consider that a speech recognition device may prove usable for our purposes. In fact, Interstate Electronics Corporation now markets a single chip voice recognition device (VRC008) which is capable of reliable and independent recognition of up to eight words or phrases which are stored in its vocabulary. While this may seem a minimal vocabulary it is a remarkable ability for a single chip device.

The Interstate VRC008 is capable of being trained to recognize words or phrases of up to 1.2 seconds duration.

To implement an audio signal recognition scheme would require that we somehow "sample" our input audio environment in discrete blocks of about one second apiece. Thus we would simulate a discrete utterance which could be processed by the circuit. In the absence of the characteristic APU signal the device would register no recognition of the input sample. But after APU ignition it is reasonable to assume that the device would treat the APU signal as a recognizable "word" it had previously been taught.

While this approach may seem at first to be a promising one we must also consider the drawbacks, especially in view of the technically simpler approaches we have reviewed so far. First is the cost. Although the Interstate chip is by itself a relatively inexpensive device (on the order of ten dollars in quantity), by itself it is also useless without a twenty-five thousand dollar training and development tool. The intent of the manufacturer is that the cost of the development tool will be amortized by the consumer over a sizable run of usable end devices. Our application does not lend itself to mass production and the cost therefore becomes prohibitive. This is especially true in view of the cost of the simpler technologies discussed in previous chapters which have given us useful designs.

Another drawback of a speech recognition approach is the level of technical complexity versus guarantee of successful results. Unless we use a device of modular circuit size or

smaller we risk an excess of power and space consumption. But the state of the art in speech recognition is such that accuracy of recognition is roughly related to the size of the device (although it is directly the vocabulary size which is the truly overwhelming factor here). The Interstate VRC008 claims only an 85 percent accuracy of recognition which is low by the standards of other speech recognition devices. This is the price one pays for small size.

The important point is that our signal of interest is characterized by extremely well-defined and stationary spectral components. This fact allows the use of cheaper and more traditional methods of signal processing and filter design. Were our signal of a rapidly time varying nature then a purely analog approach would be impossible, and even a digital approach would prove difficult if not infeasible. It is then that methods of linear predictive coding which form the basis of speech recognition would become one of a very few viable alternatives.

VII. CONCLUSION

In this thesis I have considered several approaches to the problem of designing a matched filter for the detection of the acoustic signal which characterizes the Shuttle Auxiliary Power Unit. The Analog and Digital IIR filter approaches were treated in some detail, while the Weiner FIR and Voice Recognition methods were given less attention. My purpose was not to present an exhaustive treatise on the subject of filter design, but rather to describe various ways in which a particular problem might be approached.

It is not coincidental that the order of presentation of the considered methods should conform to the chronological introduction of these sciences to the engineering community. As may be expected, the facility with which each of these methods is employed is proportional to their general familiarity among engineers. The analog approach considered first is the best established method of filter design. Not surprisingly, this method is supported by a wealth of literature. Despite this ample documentation, at best the analog approach to filter design is an inexact science which is largely dependent upon the degree to which one is able to characterize the signals we wish to manipulate. Often, however, we have excellent knowledge of these signals, and thus the analog approach to filter design remains a

completely reasonable and certainly cost effective approach to simple filter designs.

The APU signal of concern to this study was such a signal. Its signature was stationary over time and could be reliably found at amplitudes well above the noise threshold. The dominant component at 600 Hz was of quality sufficient to preclude examination of sub-dominant spectral harmonics at higher frequencies. The fact that a well-defined signal was evident allowed for a design which emphasized the simplicity of the analog approach.

Mention should be made of the obstacles which did impede the final analog design. Because an analog filter serves only to attenuate those signal component spectral elements out of the passband, but does not eliminate them, it is necessary to know the range of amplitude which may be expected of the sensor microphone output. For a given amplitude of signal input which varies little within the range of input frequencies it may be reliably expected that the analog bandpass filter would reject the frequency components outside of the narrow passband. But if the spectral components were grossly disparate in their amplitude and a component out of the passband were received which was significantly above the amplitude expected of the 600 Hz center frequency, then it is possible that the component out of the passband would be passed regardless of

the filter attenuation. This demonstrates the need we have to know the nature of the input signal.

One approach to this problem is to increase the attenuation of the filter. But this does not guarantee signal component rejection out of the passband. The solution for an analog approach lies in Automatic Gain Control (AGC) at the sensor microphone input to the filter. In this manner we can ensure a dynamic range of input signal which is within the limits of filter discrimination. This implies a careful selection of a microphone and preamplifier combination which in turn implies a similarly careful understanding of the dynamic range of the input signal. Indeed, these considerations continue to be the most vexing aspects of a useful final design. The actual dynamic range of the signals recorded on tape was unreliable due to the number of intermediate and indeterminate dubs which the tape underwent prior to our acquisition of a copy.

Furthermore, and even more importantly, the ultimate placement of the sensor microphone in the Shuttle cargo bay will have considerable effect upon the nature of the signal available for discrimination. It will also tell significantly on the dynamic range. This factor will impact upon any chosen filter design regardless of the algorithm selected. Thus in the analog case we must design for a wide dynamic range and provide AGC which yields a narrower range of amplitude input into the filter.

Much of this problem is overcome with the digital filter implementation developed in Chapters 4 and 5. At the foundation of the digital design is a frequency domain scheme whose output is less dependent upon input amplitude variations than the frequency components of the input signal. In fact using an EPROM based filter design such as afforded by the INTEL 2920 we enjoy considerable flexibility in tailoring the range of allowable inputs and outputs through careful selection of program parameters. The limitations are rather imposed by the noise level at the low end and the power limit at the high end.

There are several drawbacks to the digital filter which bear mentioning. The foremost drawback is cost relative to the analog filter. The design presented in Chapter 5 was dependent upon the SDK-2920 Development Kit which is a thousand dollar item. This is the minimum hardware which is necessary to develop a 2920 signal processing design. However, to support any sort of a sophisticated development requires the INTEL Intellec Development System with associated software. This quickly elevates the expense of the system to a range of tens of thousands. Of course there are certainly more uses for the Intellec system than simply a 2920 development application, so this expense can be amortized over those additional uses. But the 2920 applications software which supports the Intellec system is a four thousand dollar expense by itself.

This fact proved significant to the digital design when the simulator software was found to have a bug in it. When the original disks could not be located it was then deemed more practical to develop an application specific simulation on a mainframe computer instead of purchasing a replacement package from INTEL. This meant an additional expenditure of time of course, and was only successful in showing the adequacy of the specific 2920 filter implementation algorithm. However, without the 2920 Simulator software package effective troubleshooting was made significantly more difficult. Nontheless, as indicated in the results of Chapter 5, a successful 2920 implementation was accomplished without a fully healthy simulator. With it the design process would have been considerably more efficient.

An additional consideration is the complexity of the digital design over the analog approach. This is due in large part to the availability of resources which support an analog design relative to the novel approach represented by a state-of-the-art signal processing chip. However, the complexity of a signal processor application is often far outweighed by the considerable flexibility which it provides. One must not forget the power of the 2920 (witness its ability to incorporate all of the hardware elements of the follow-on logic circuitry required in the analog design in but a dozen or so lines of 2920 assembly language code) and weigh this against the short term

inconvenience of having to become acquainted with a new approach. Once mastered the significant ability of a signal processing device make an analog approach to any complex filter design seem archaic. In addition the fewer actual circuit components required in an EPROM based device means significant savings in power consumption. This is an especially noteworthy item when considering an electronic device for a space application.

For the purposes of this thesis I must admit that the 2920 was certainly fun to work with. The literature is sketchy in spots and several calls to technical support at INTEL were needed to resolve some issues and errors. But overall the 2920 certainly provides the researcher with a significant amount of flexible and powerful signal processing ability.

The significant advantage of implementing a digital filter over the analog design is the relative immunity to the variations in input amplitude. This was a crucial consideration in the development described in Chapter 5 and by itself would account for the choice of the digital design over the analog approach. When coupled with the further advantages of lower power consumption, less physical space required and considerable flexibility in accommodating future changes without the need for hardware modification, the digital approach implemented in a powerful signal processor becomes an irresistable filter design option.

In Chapter 6 we considered two other approaches to the APU signal detection problem. Unfortunately a lack of time prohibited a serious examination of these additional approaches. Both are well-founded and represent the leading edge of signal processing technology. Given a requirement for detection of a more complex signal than we considered in this paper, these latter methodological options could well represent the only viable means of processing a time-varying signal in the acoustic spectrum.

APPENDIX B

POWER SPECTRAL DENSITY PLOTS OF THE SHUTTLE
CARGO BAY PRE-LAUNCH ACOUSTIC ENVIRONMENT

Legend for the Graphical Output on the Following Pages

Shuttle Flight Number: STS-2, STS-3 or STS-4

. Microphone Identification: 9405, 9219 or 9403

Sampled Interval Relative to APU Power-Up: PRE or POST

All PSD Sources are from the Original Aerospace Tape
Copies (labelled ORIG)

Narrow Band Analysis (N=40 Samples)

Hanning Weighting

5.0 Volt RMS Front End Limiter

Gain: 10 dB per division

Cursor Point Label: X (Hz) and Y(B) (Engineering Units)

Scale: Linear Ordinate (0-2000 kHz)
         Logarithmic Abcissa (10^1 to 10^8 EU)

RUN IDENTIFICATION ___ APU HOTFIRE CHANNEL 10   STS-2 _____

PARAMETER ___ D0281A ___ Noise Floor ___   TEST DATE _ 15 September 81 _____
OVERALL RMS VALUE 0.1905 G's ___   ANALYSIS B W ___ 2.2467 Hz ___
ENGINEERING UNITS 30.0000 G's ___   ANALOG L.P. FILTER B W 2300.0000 Hz
START TIME: (HR: MIN: SEC) 258/12:04:20   DEGREES OF FREEDOM __ 9.0000 ___
SAMPLE RATE (S/SEC) 6134.9687 ___   PROCESS DATE __ 18 September 81 ___

VERTICAL SCALE FACTOR: TRUE VALUE • VALUE X 10 TO THE POWER OF _-5_

HERTZ

120
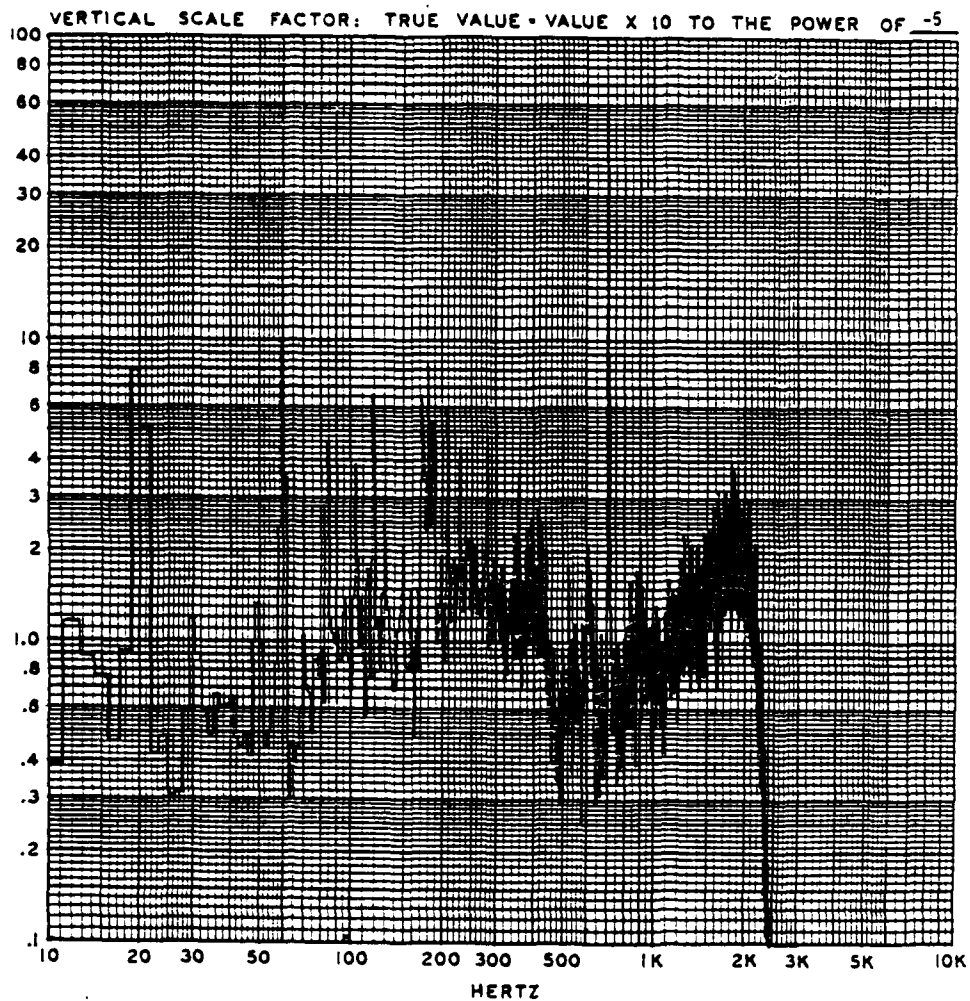
RUN IDENTIFICATION APU HOTFIRE CHANNEL 10 STS-2

PARAMETER ____00281A____   TEST DATE ____15 September 81____
OVERALL RMS VALUE 2.7251 G's   ANALYSIS B W _2.2467 Hz_
ENGINEERING UNITS _30.0000 G's_   ANALOG L.P. FILTER B W _2300.0000 Hz_
START TIME: (HR: MIN: SEC) 258/12:03:20   DEGREES OF FREEDOM _9.0000_
SAMPLE RATE (S/SEC)_6134.9687_   PROCESS DATE ____18 September 81____

VERTICAL SCALE FACTOR: TRUE VALUE = VALUE X 10 TO THE POWER OF _-3_

HERTZ

119
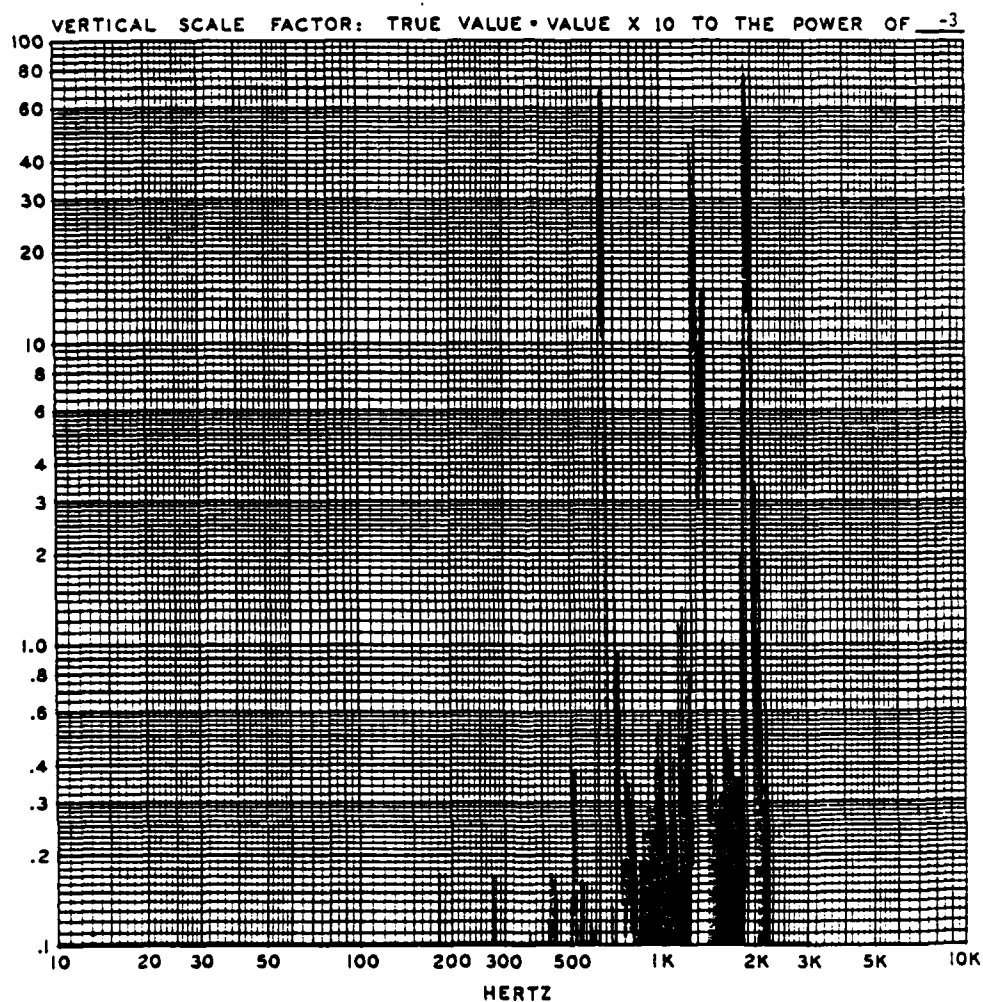
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ENGINEERING UNITS ___30.0000 G's___   ANALOG L.R. FILTER B W ___2300.0000 Hz___
START TIME: (HR: MIN: SEC) ___258/12:01:22___   DEGREES OF FREEDOM ___9.0000___
SAMPLE RATE (S/SEC) ___6134.9687___   PROCESS DATE ___18 September 81___

VERTICAL SCALE FACTOR: TRUE VALUE = VALUE X 10 TO THE POWER OF ___-2___

HERTZ

118
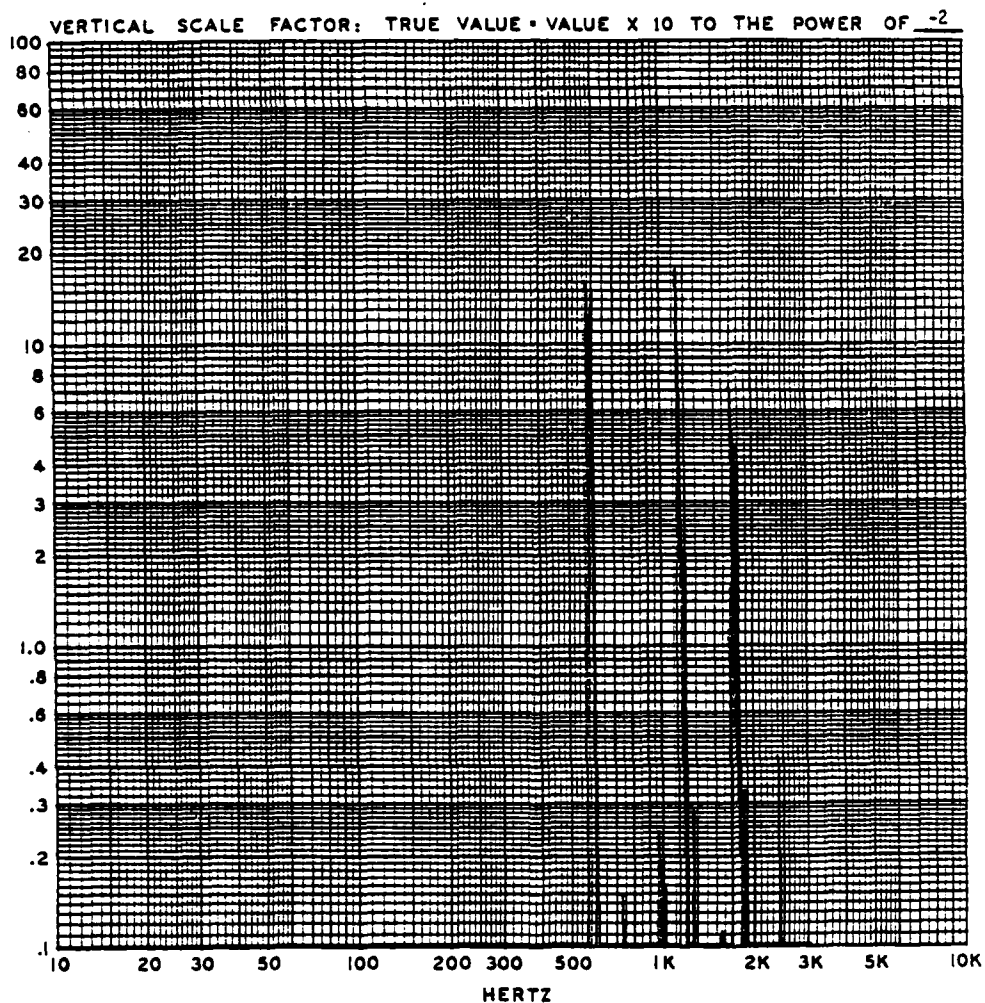
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PARAMETER____D0281A   TEST DATE ____15 September 81
OVERALL RMS VALUE 6.4787 G's   ANALYSIS B W ___2.2467 Hz
ENGINEERING UNITS _30.0000 G's   ANALOG L.P. FILTER B W 2300.0000 Hz
START TIME: (HR: MIN: SEC) 258/11:56:35   DEGREES OF FREEDOM ___9.0000
SAMPLE RATE (S/SEC)___6134.9687   PROCESS DATE ___18 September 81

VERTICAL SCALE FACTOR: TRUE VALUE • VALUE X 10 TO THE POWER OF $^{-1}$

HERTZ
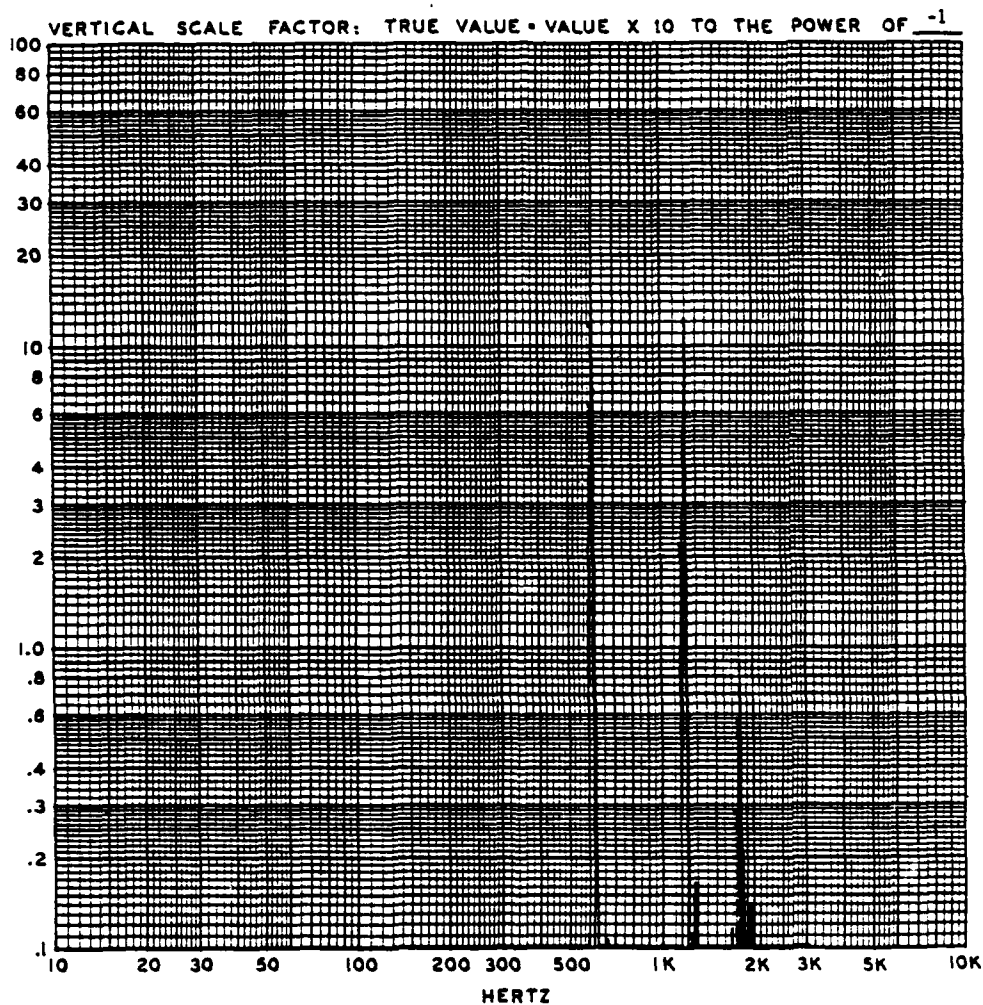
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ENGINEERING UNITS ___30.0000 G's___	ANALOG L.P. FILTER B W ___2300.0000 Hz___
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SAMPLE RATE (S/SEC) ___6134.9687___	PROCESS DATE ___18 September 81___

VERTICAL SCALE FACTOR: TRUE VALUE • VALUE X 10 TO THE POWER OF -2

116
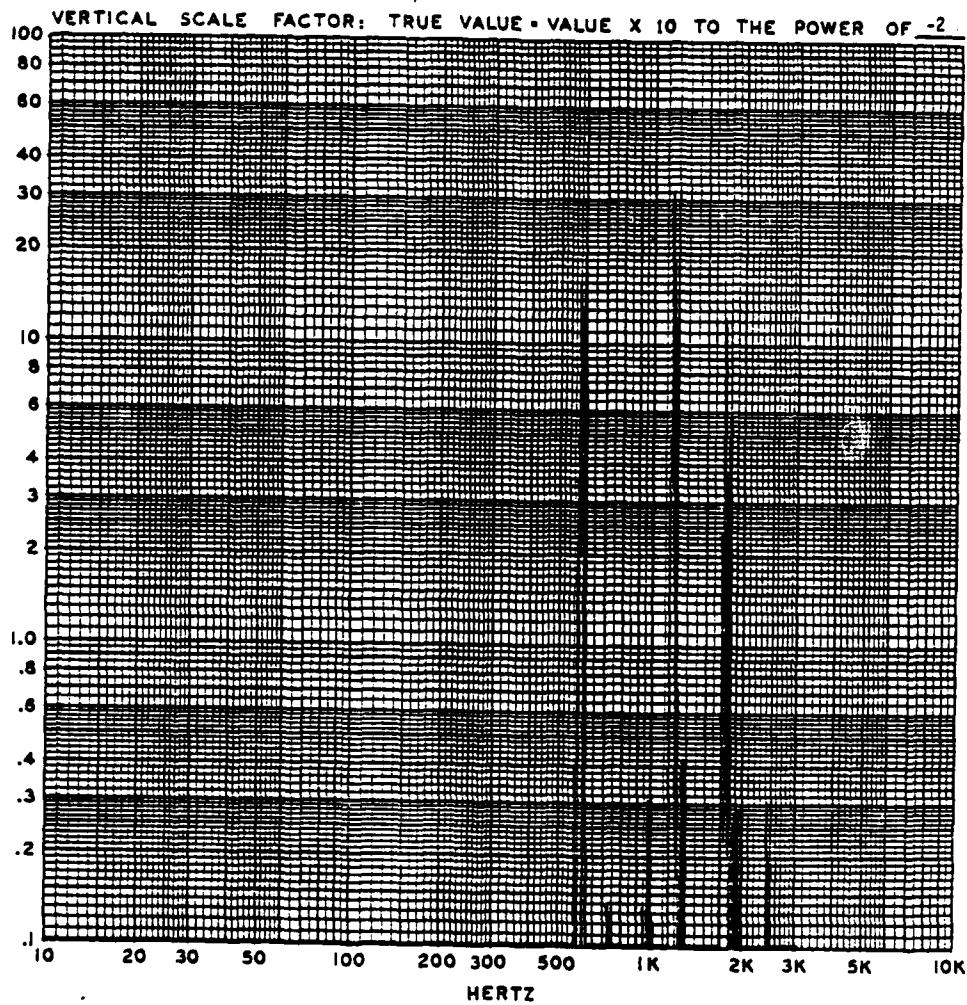
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PARAMETER <u>00281A</u>   TEST DATE <u>15 September 81</u>
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ENGINEERING UNITS <u>30.0000 G's</u>   ANALOG L.P. FILTER B W <u>2300.0000 Hz</u>
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SAMPLE RATE (S/SEC) <u>6134.9687</u>   PROCESS DATE <u>18 September 81</u>

VERTICAL SCALE FACTOR: TRUE VALUE = VALUE X 10 TO THE POWER OF <u>-2</u>

HERTZ

115
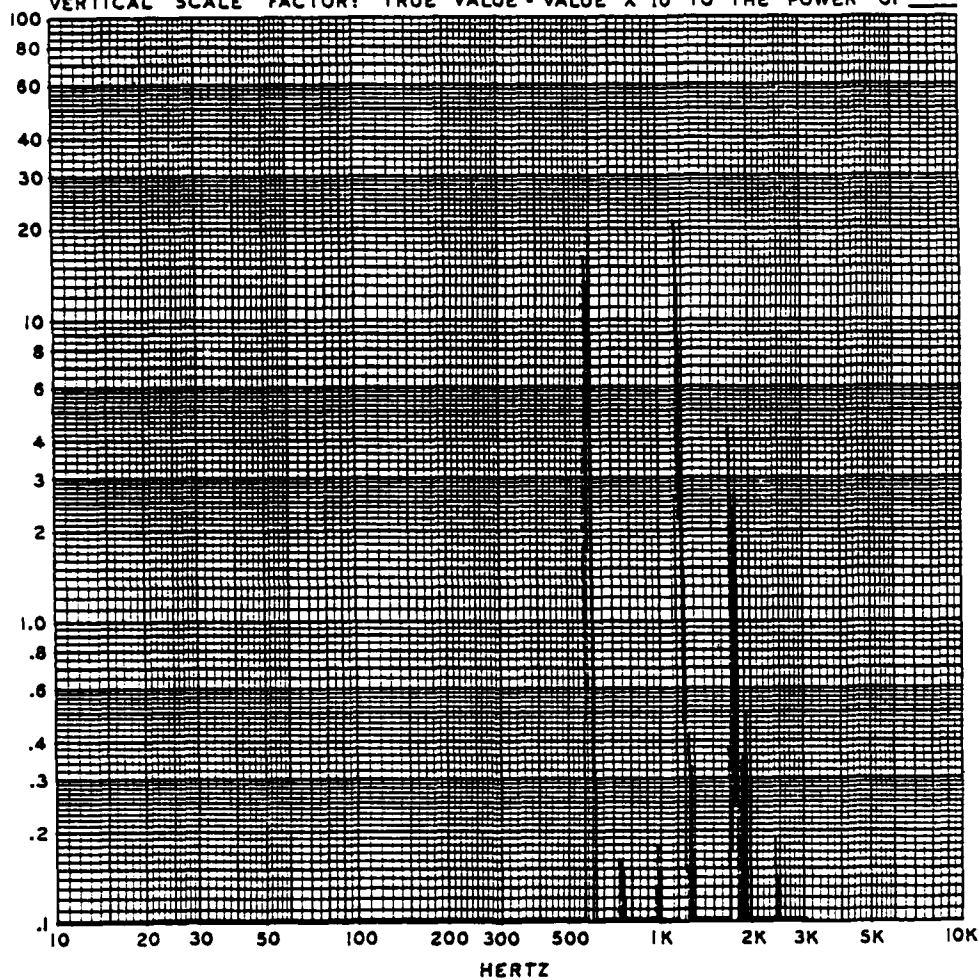
RUN IDENTIFICATION <u>APU HOTFIRE CHANNEL 11 STS-2</u>

PARAMETER <u>D0280A   Noise Floor</u>   TEST DATE <u>15 September 81</u>
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ENGINEERING UNITS <u>30.0000 Gs</u>   ANALOG L.R FILTER B W <u>2300.0000 Hz</u>
START TIME: (HR: MIN: SEC) <u>258/12:04:20</u>   DEGREES OF FREEDOM <u>9.0000</u>
SAMPLE RATE (S/SEC) <u>6134.9687</u>   PROCESS DATE <u>18 September 81</u>

VERTICAL SCALE FACTOR: TRUE VALUE = VALUE X 10 TO THE POWER OF <u>-5</u>

HERTZ

114

RUN IDENTIFICATION __APU HOTFIRE CHANNEL 11   STS-2__

PARAMETER __D0280A__   TEST DATE __15 September 81__
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ENGINEERING UNITS __30.0000 G's__   ANALOG L. P. FILTER B W __2300.0000 Hz__
START TIME: (HR: MIN: SEC) __258/12:03:20__   DEGREES OF FREEDOM __9.0000__
SAMPLE RATE (S/SEC) __6134.9687__   PROCESS DATE __18 September 81__

VERTICAL SCALE FACTOR: TRUE VALUE = VALUE X 10 TO THE POWER OF __-3__

HERTZ

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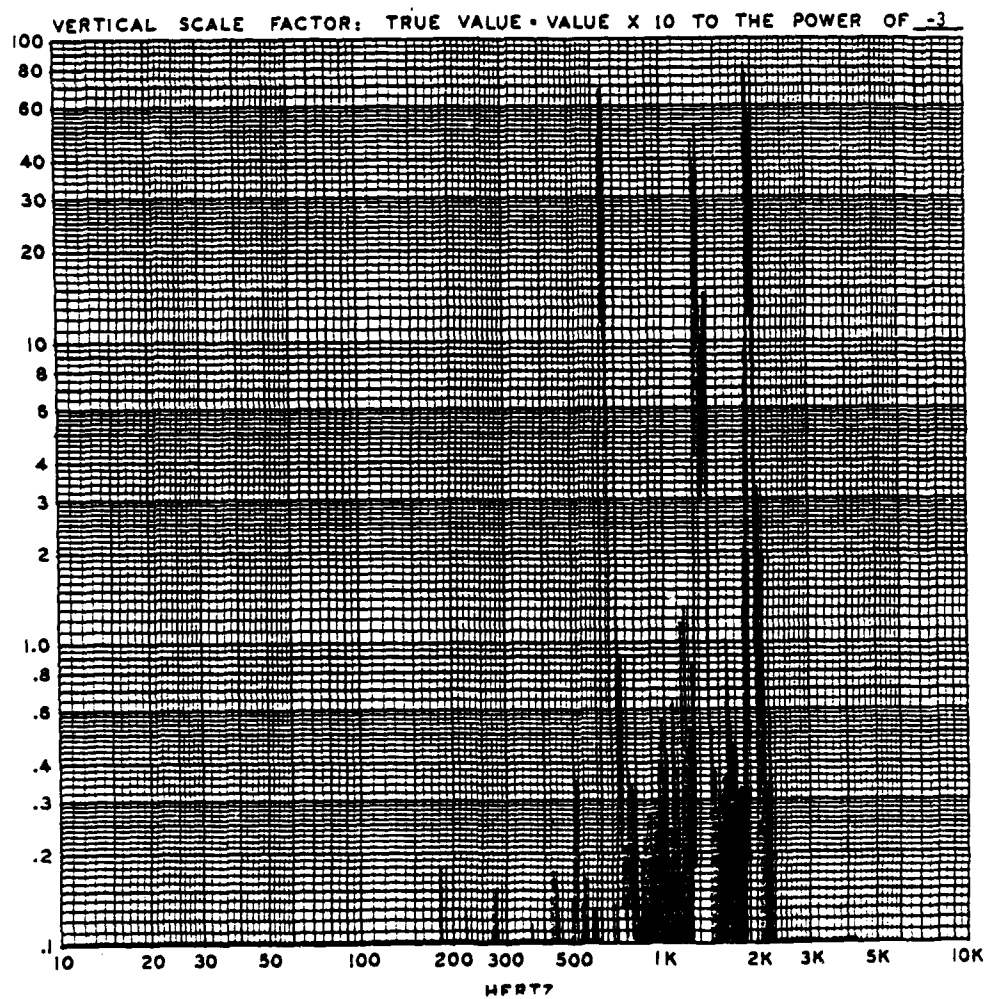
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SAMPLE RATE (S/SEC) _6134.9687___   PROCESS DATE ___18 September 81___

VERTICAL SCALE FACTOR: TRUE VALUE • VALUE X 10 TO THE POWER OF __-2__

HERTZ

112
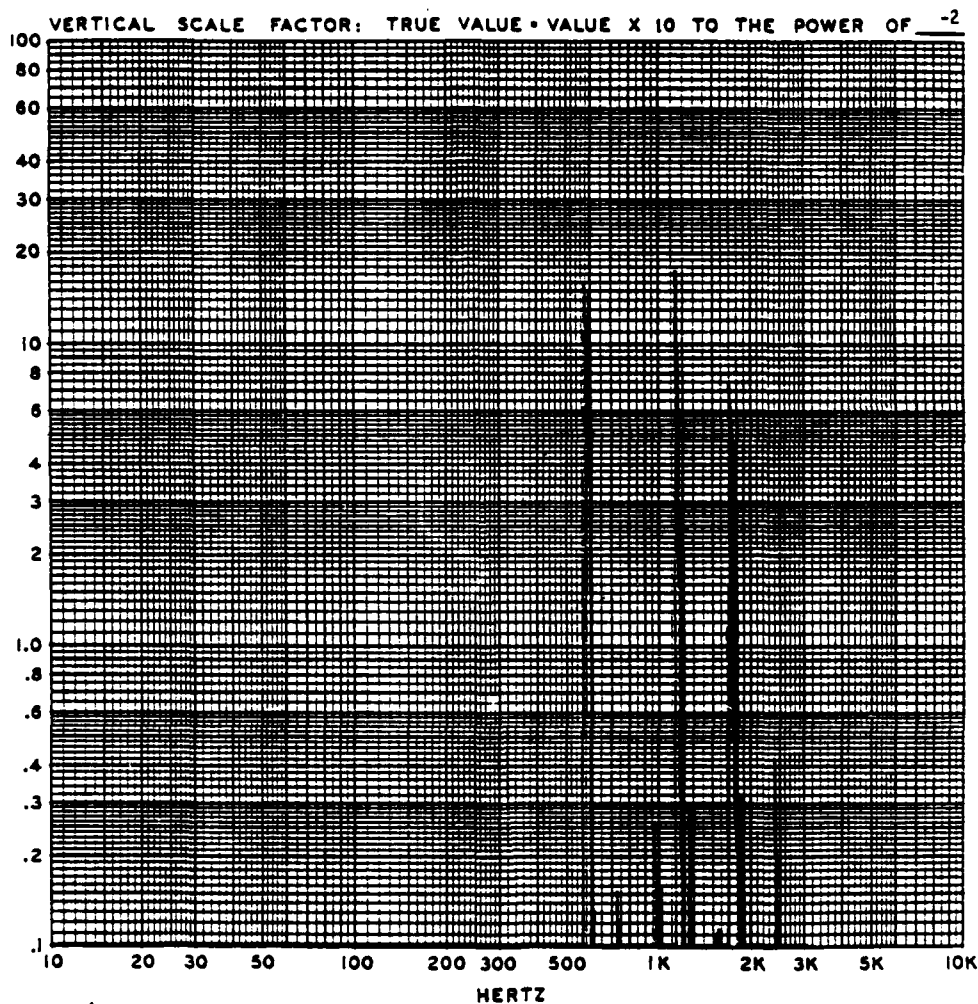
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VERTICAL SCALE FACTOR: TRUE VALUE = VALUE X 10 TO THE POWER OF $^{-2}$

HERTZ

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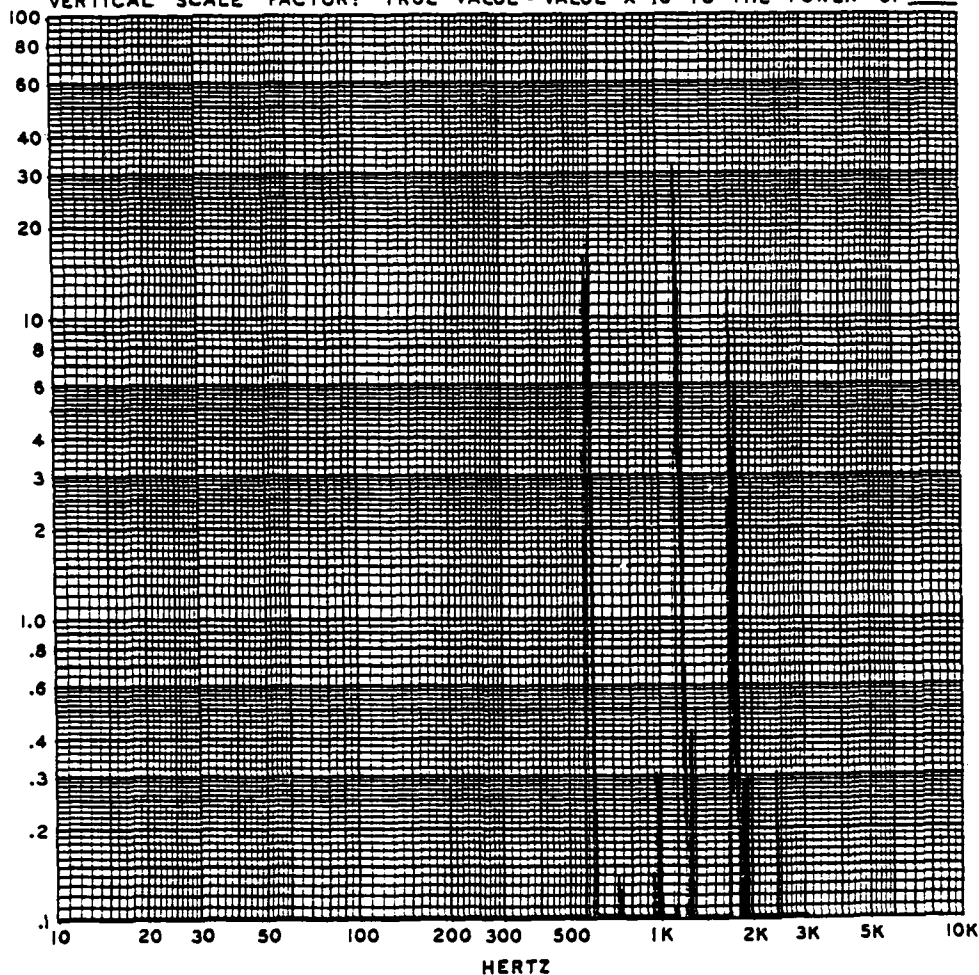
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ENGINEERING UNITS _ 30.0000 G's _____   ANALOG L. P. FILTER B W 2300.0000 Hz
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SAMPLE RATE (S/SEC) __ 6134.9687 _____   PROCESS DATE _____ 18 September 81 _____

VERTICAL SCALE FACTOR: TRUE VALUE = VALUE X 10 TO THE POWER OF _-2_

HERTZ

110
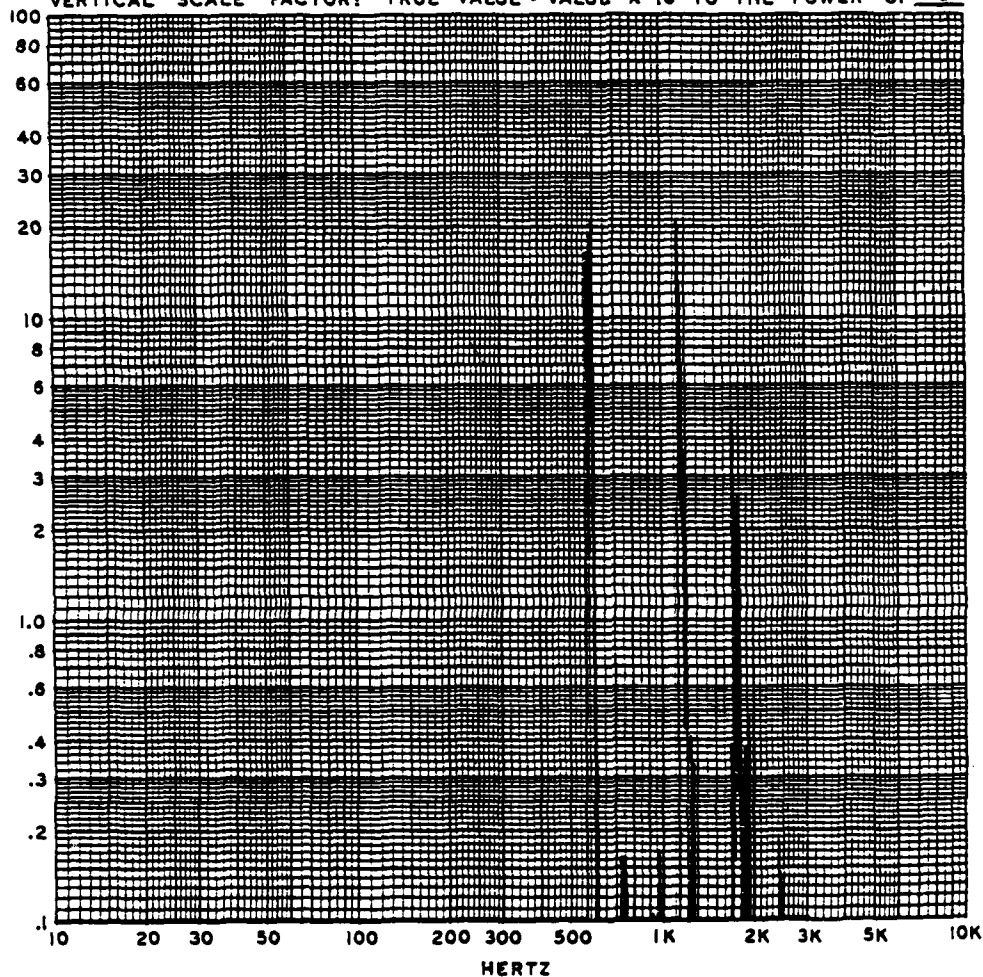
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SAMPLE RATE (S/SEC) ___ 6134.9687 ___   PROCESS DATE ___ 18 September 81 __

VERTICAL SCALE FACTOR: TRUE VALUE • VALUE X 10 TO THE POWER OF _-1_

HERTZ

109
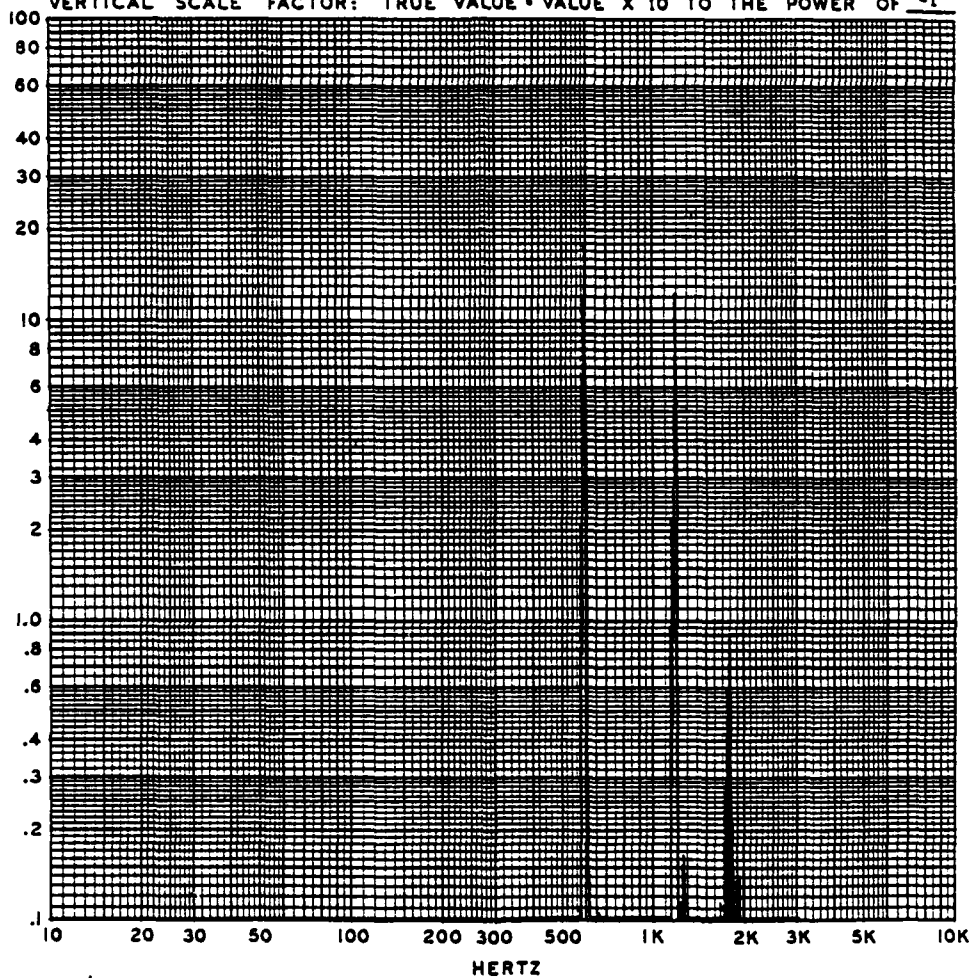
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PACKET

TEST TITLE APU HOTFIRE STS-2

TEST DATE 15 SEPTEMBER 81

RUN NO. (S)

REDUCTION DATE 18 SEPTEMBER 81

FACILITY JSC NASA VATF BLDG #49

SEQUENCE NO.(S)

DATA TYPE PSD PLOTS _APU 2 x-axis APU 2 2_ D0280A and D0281A + Noise Floor
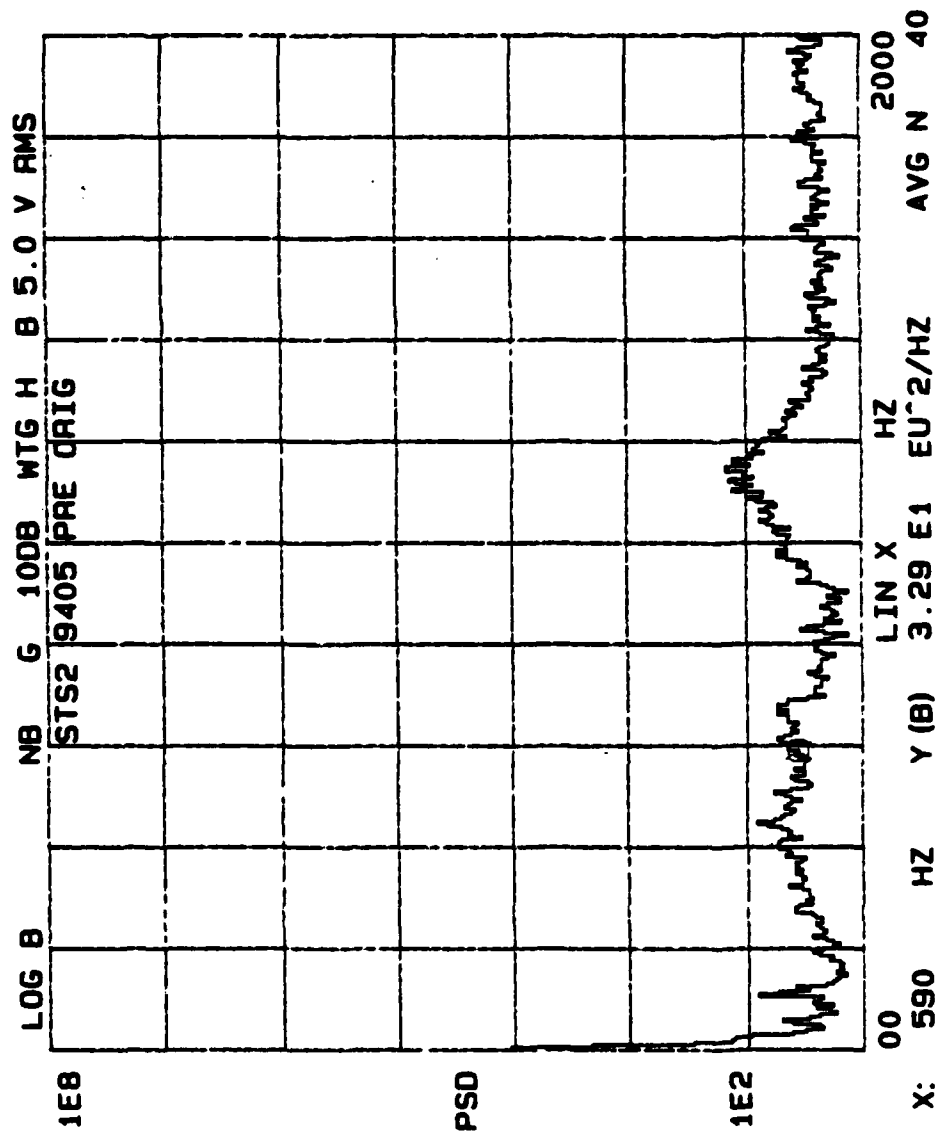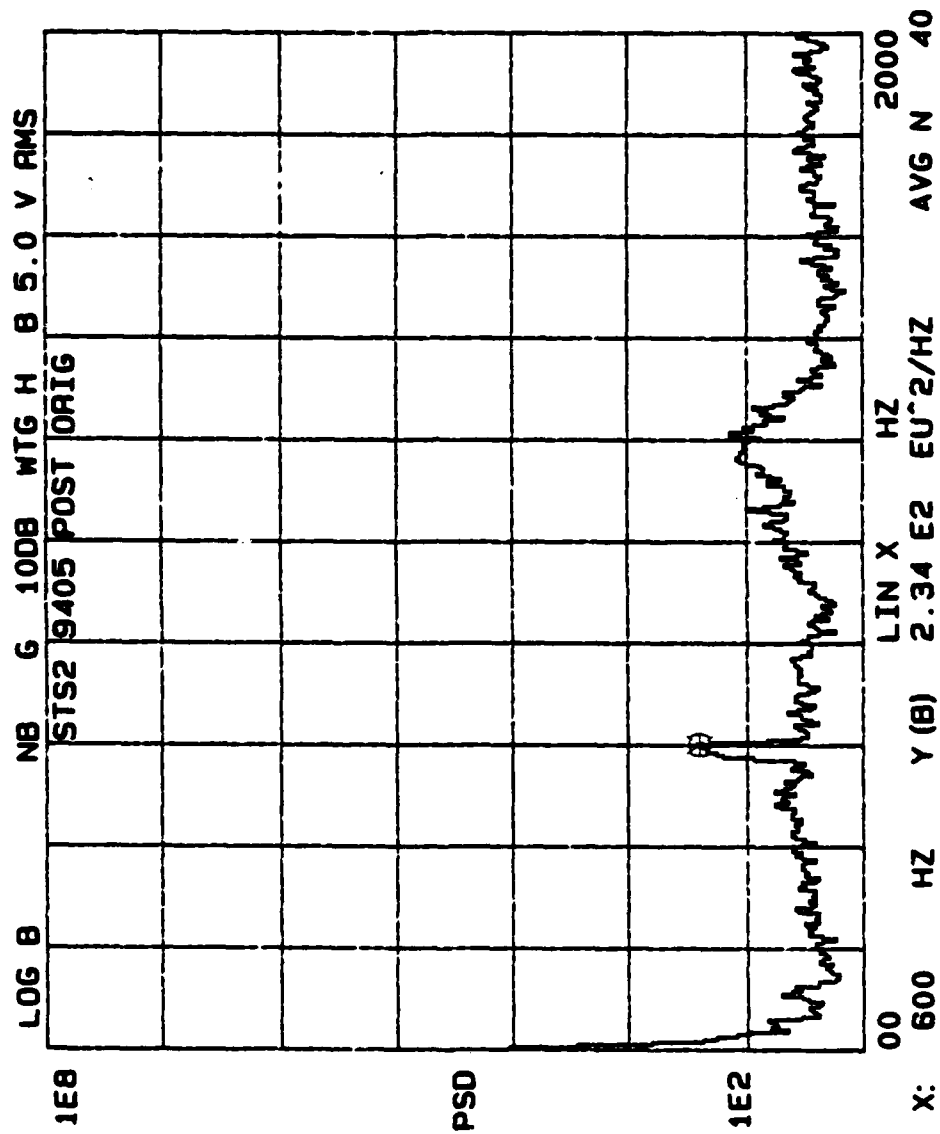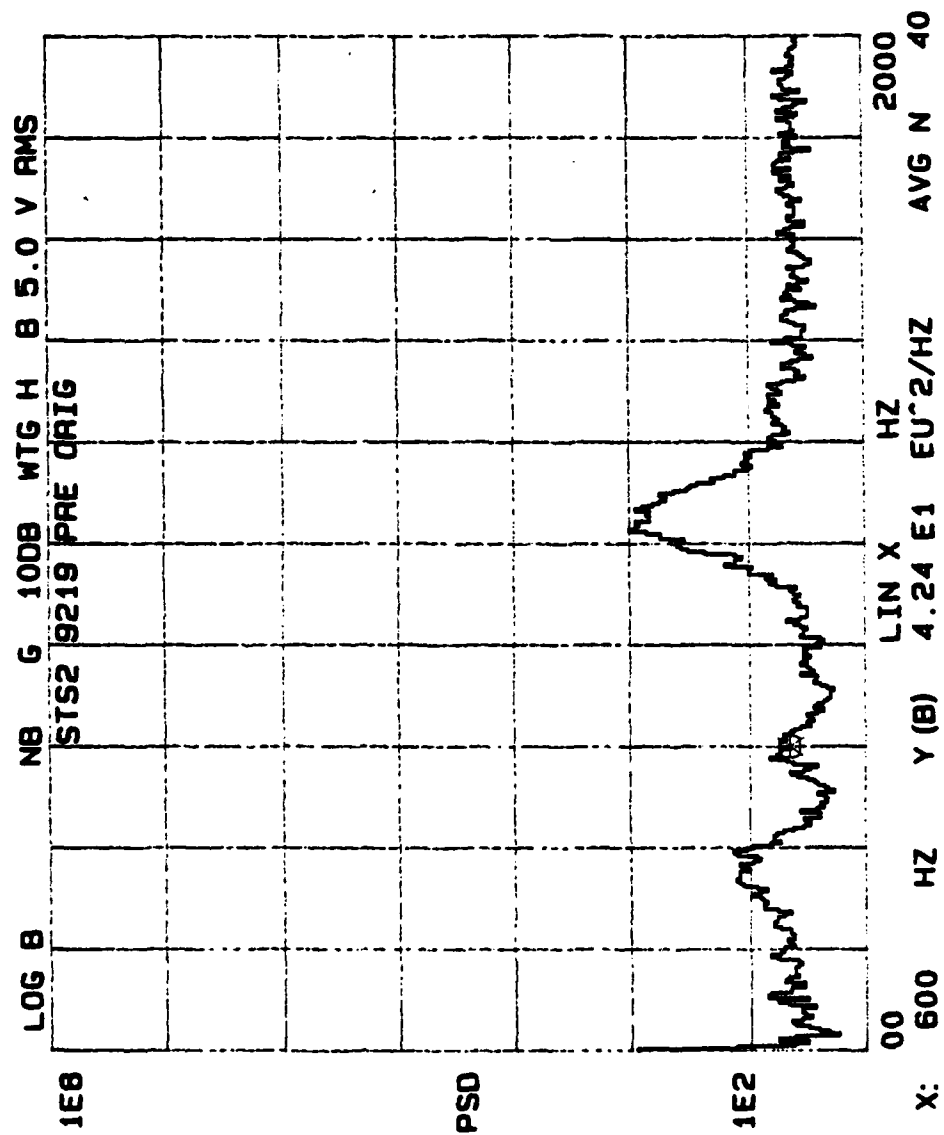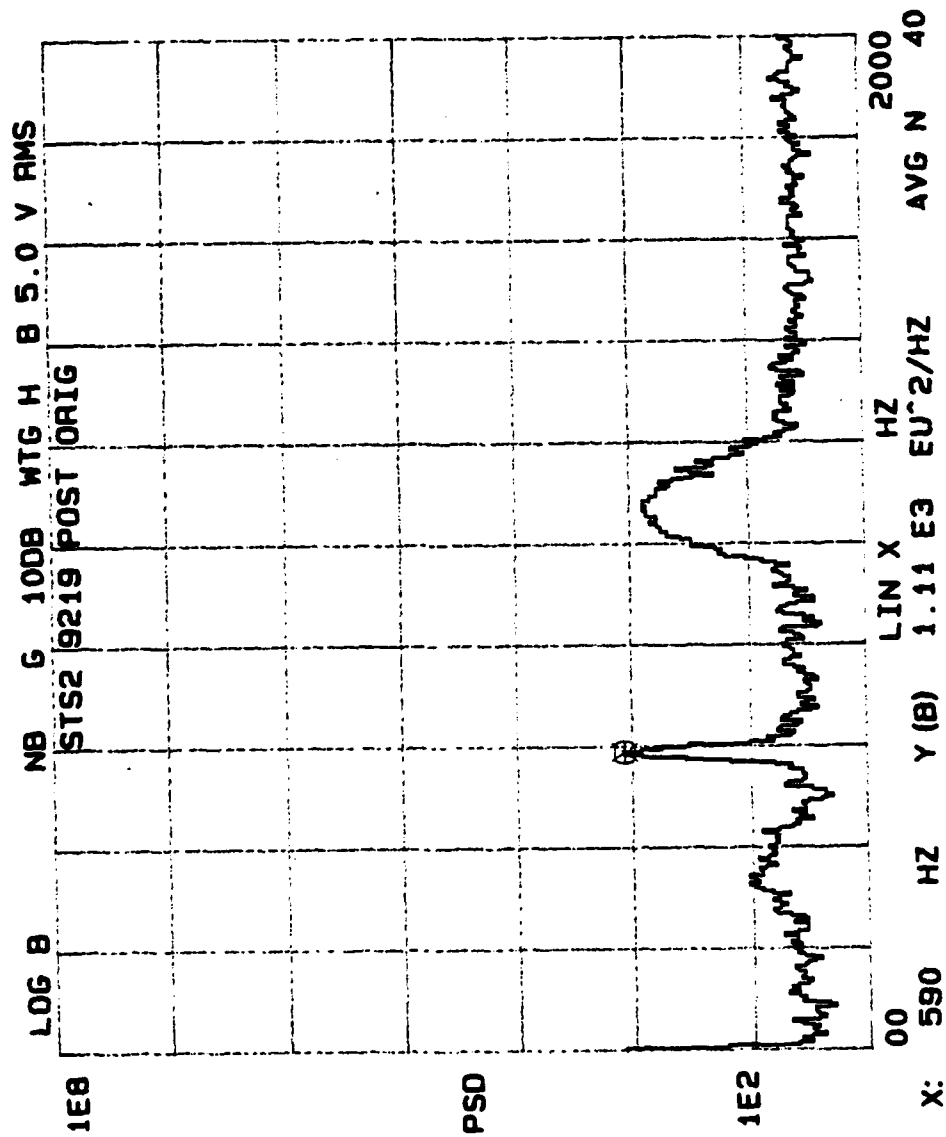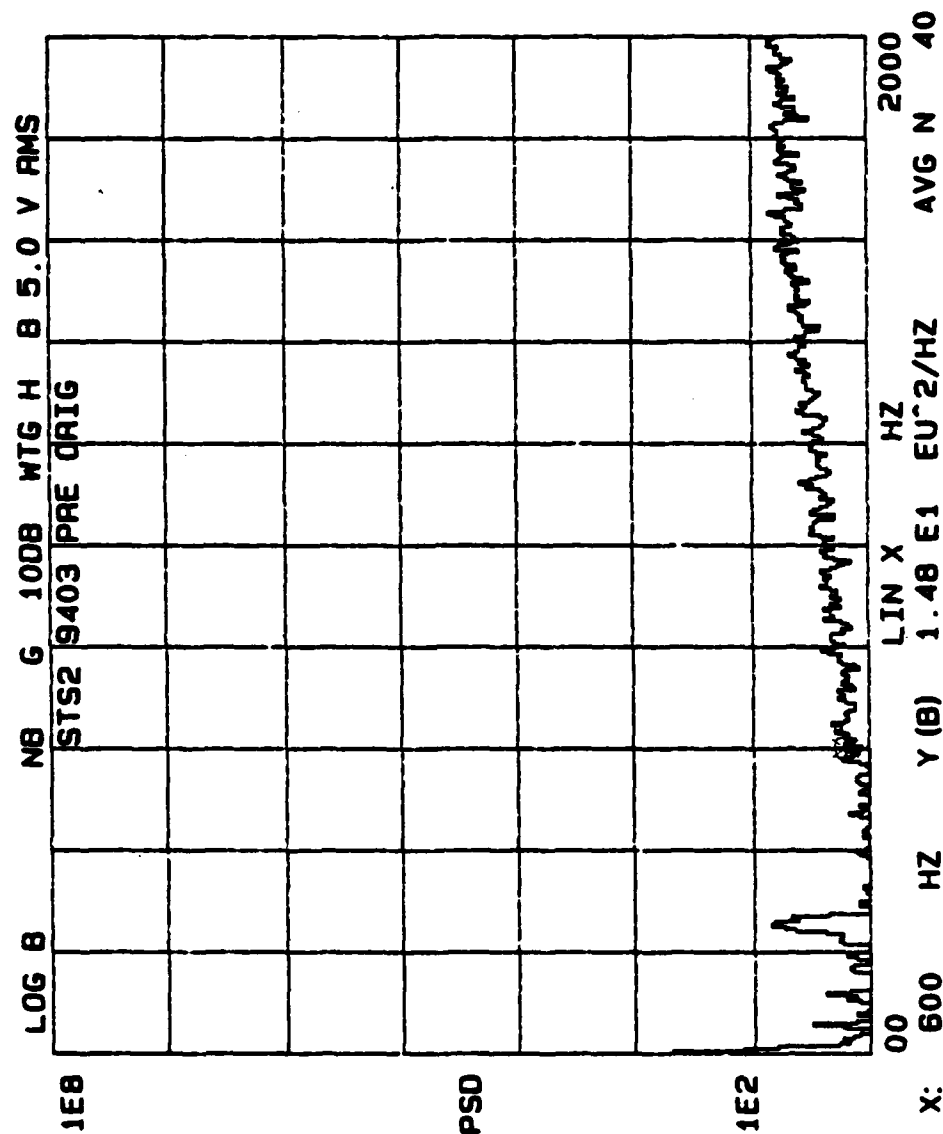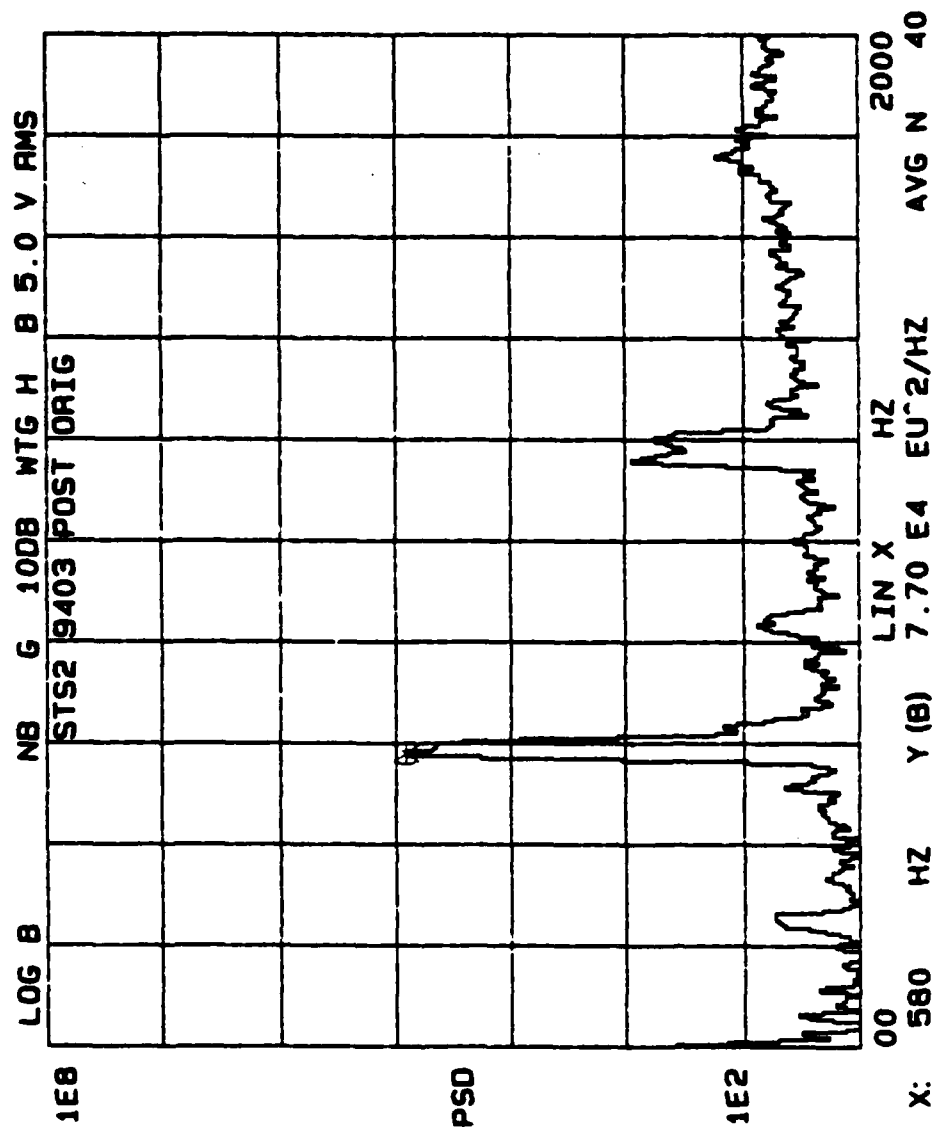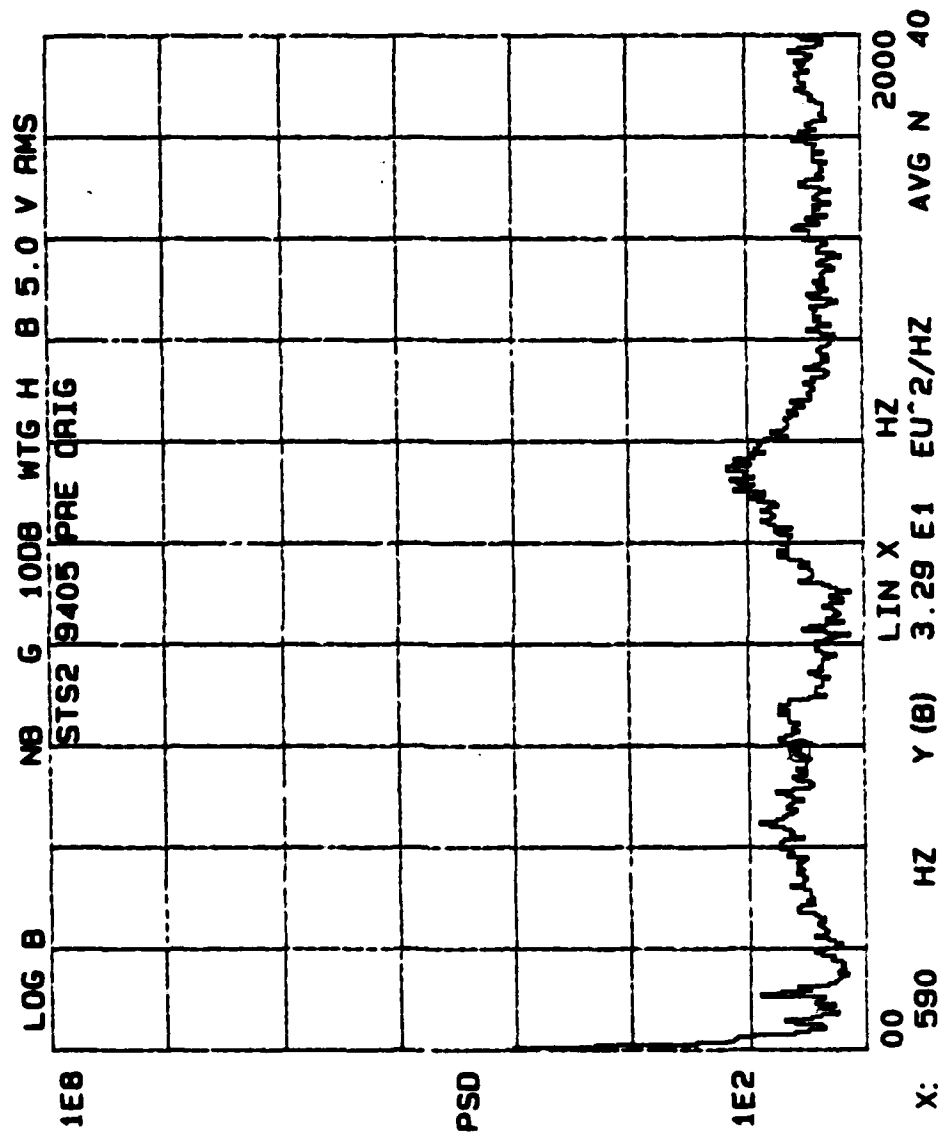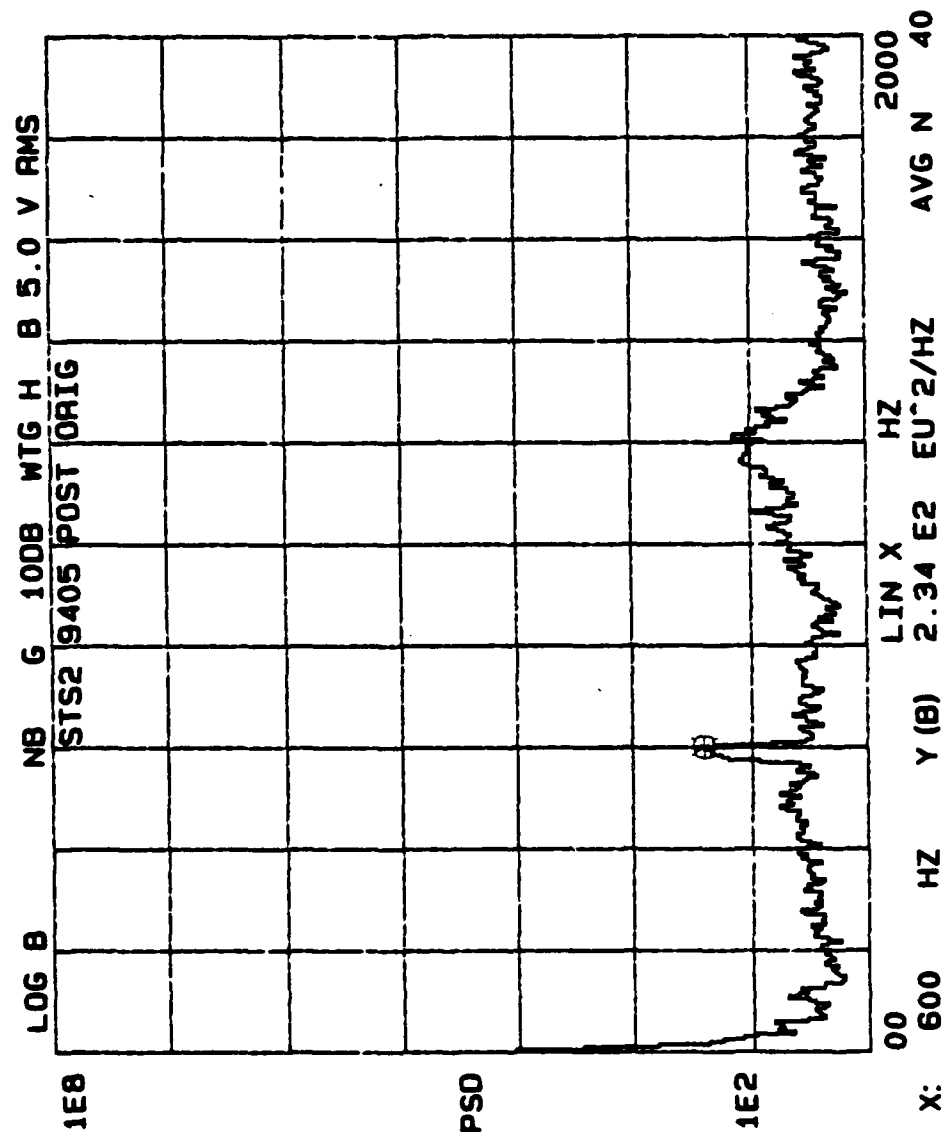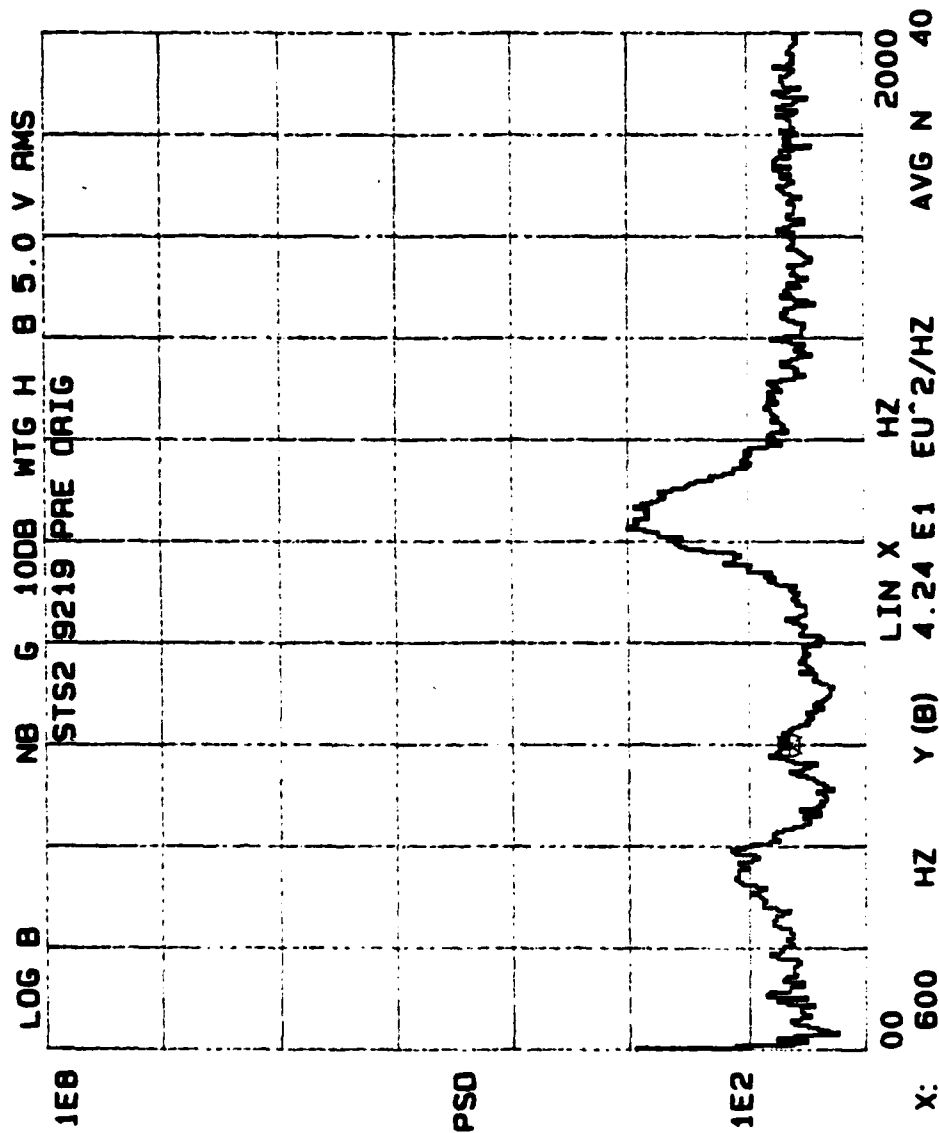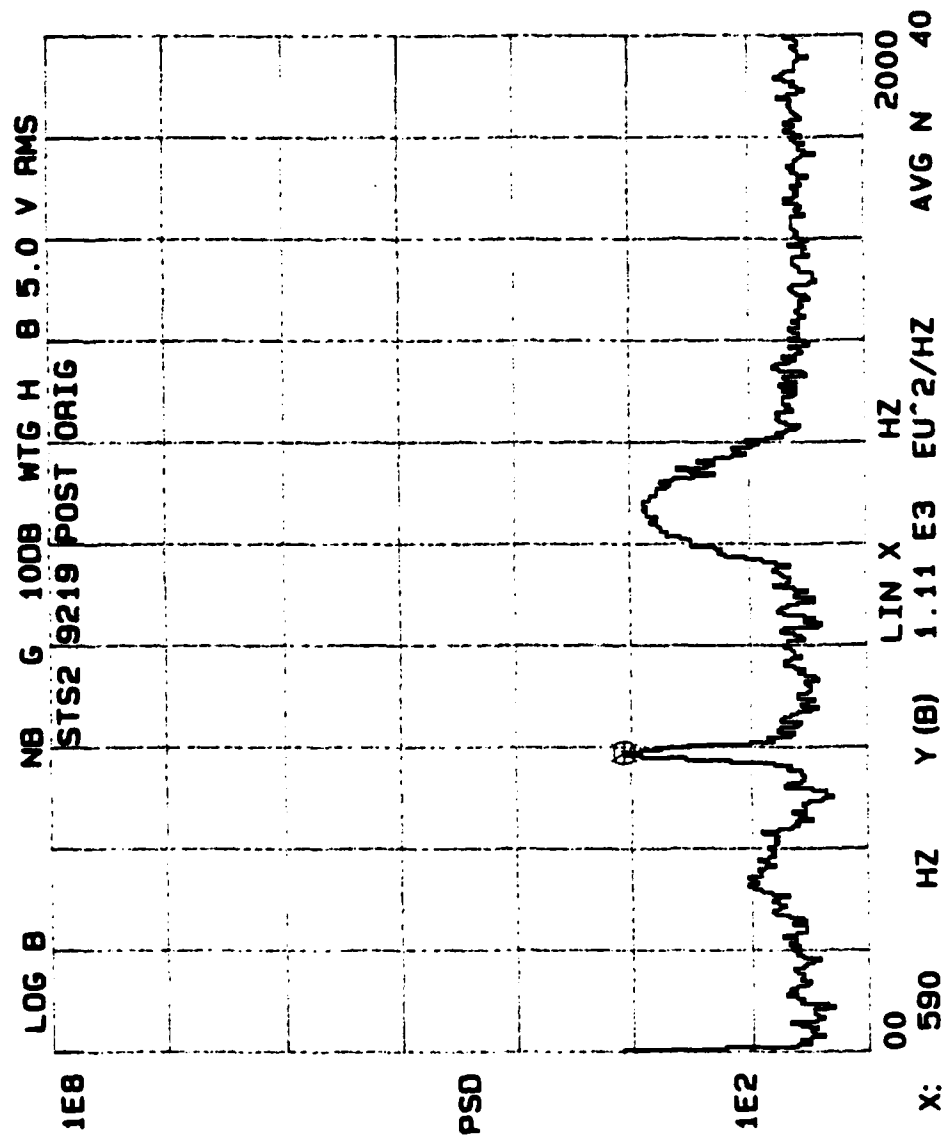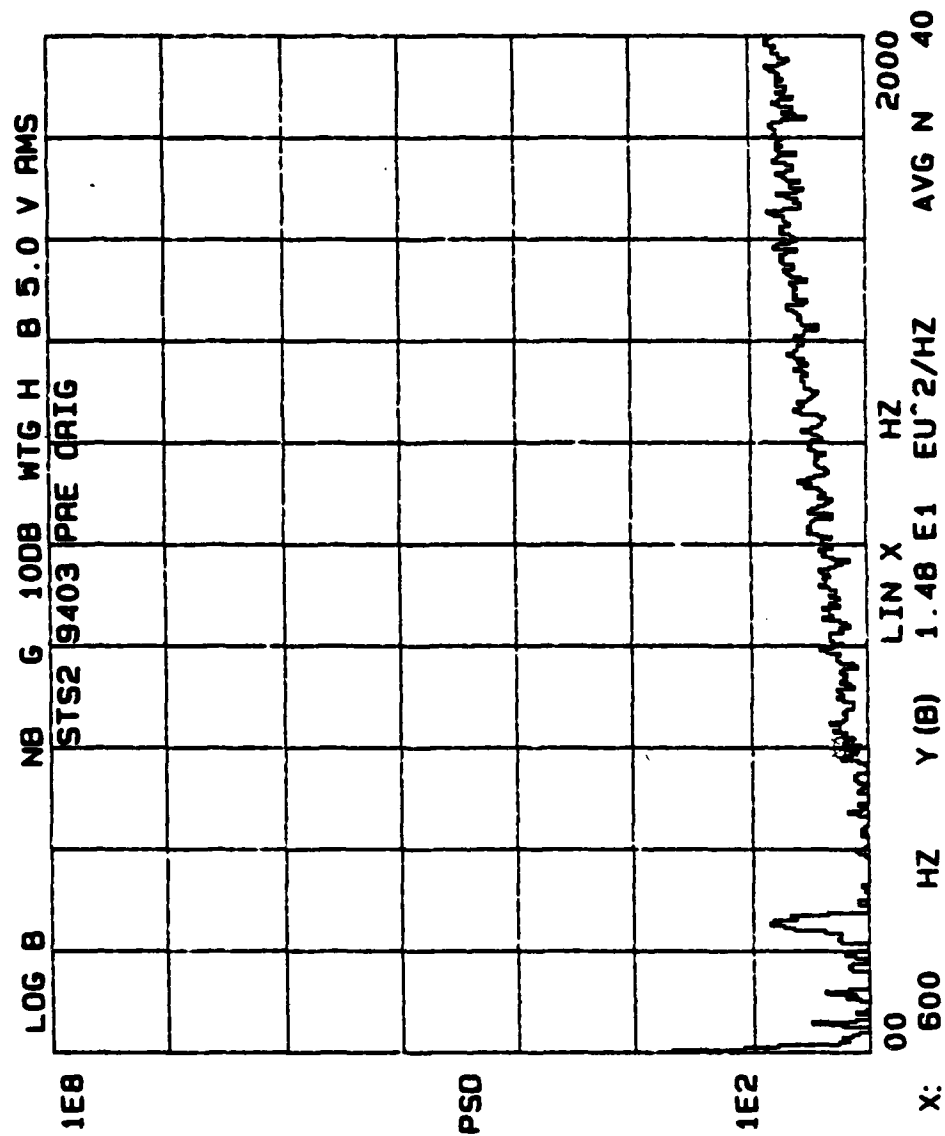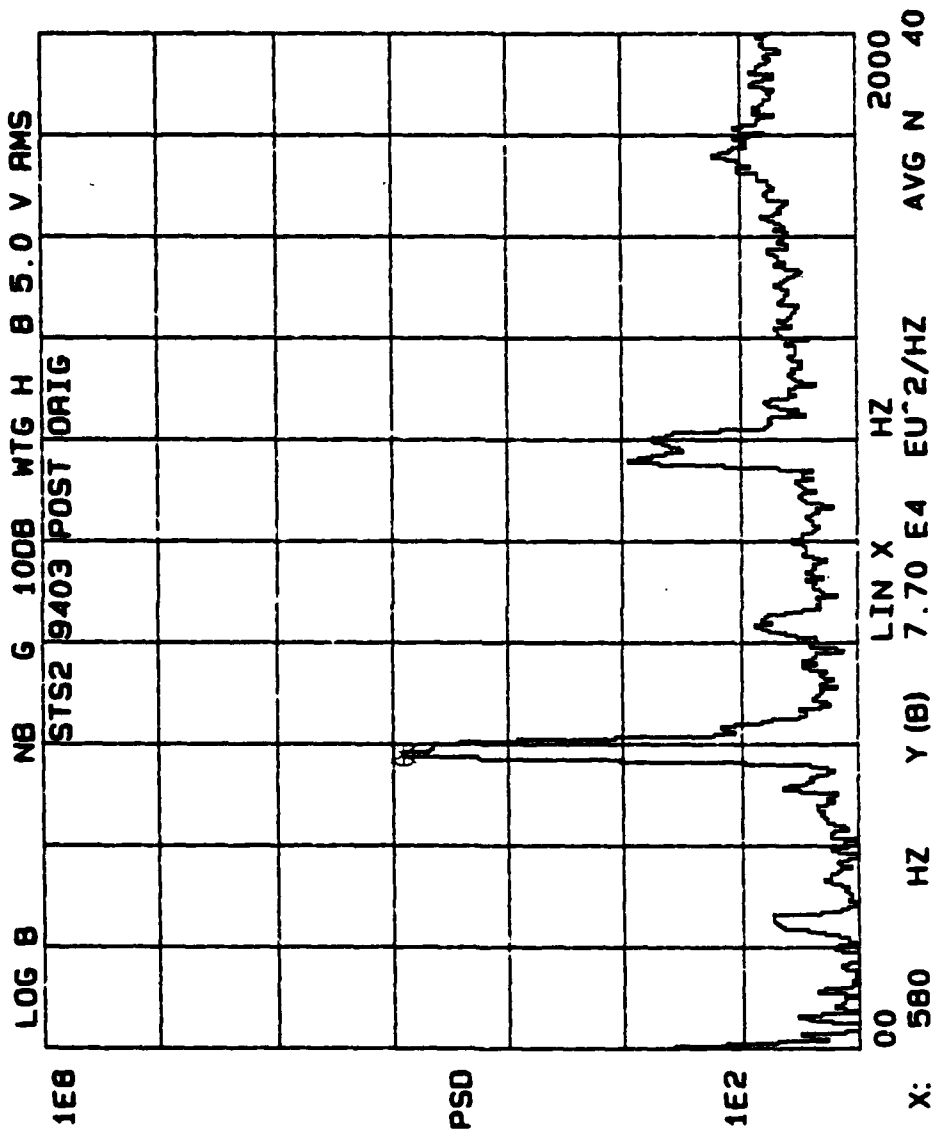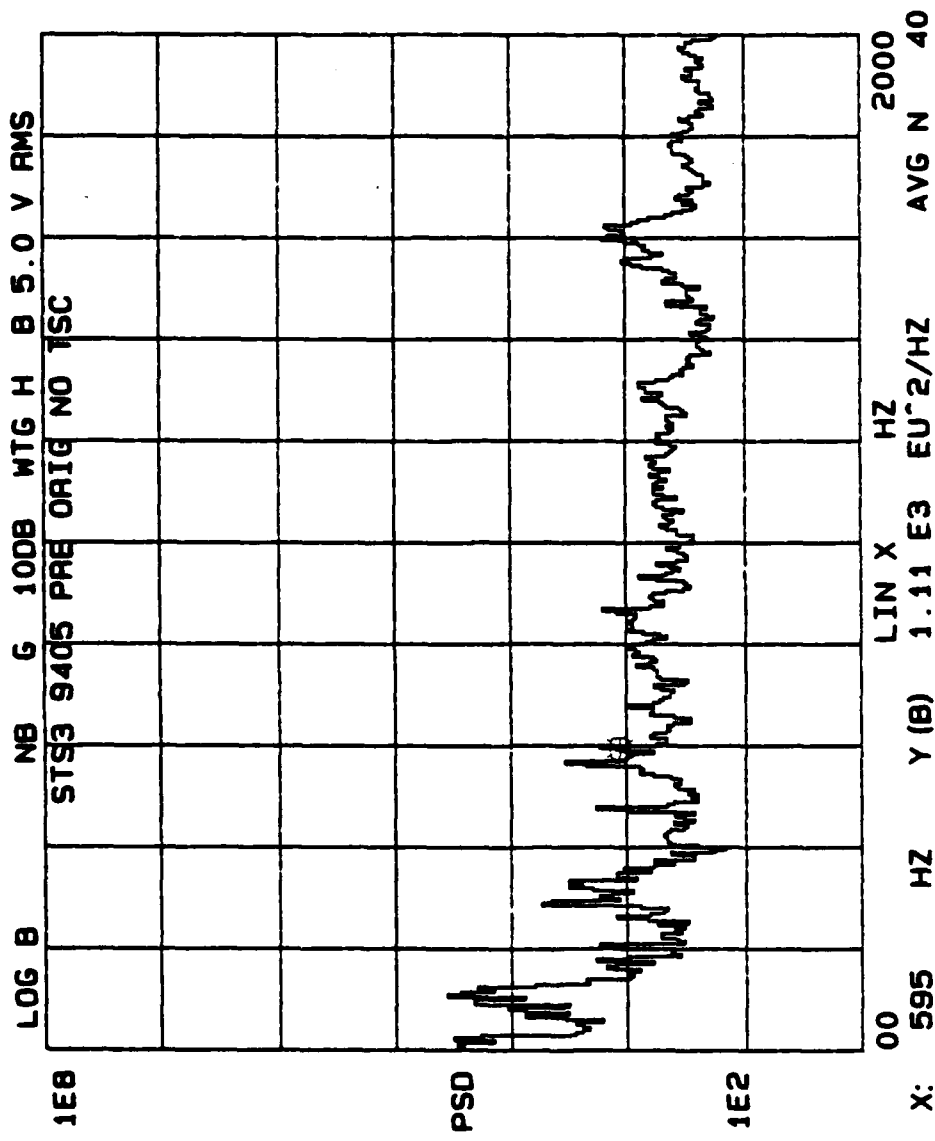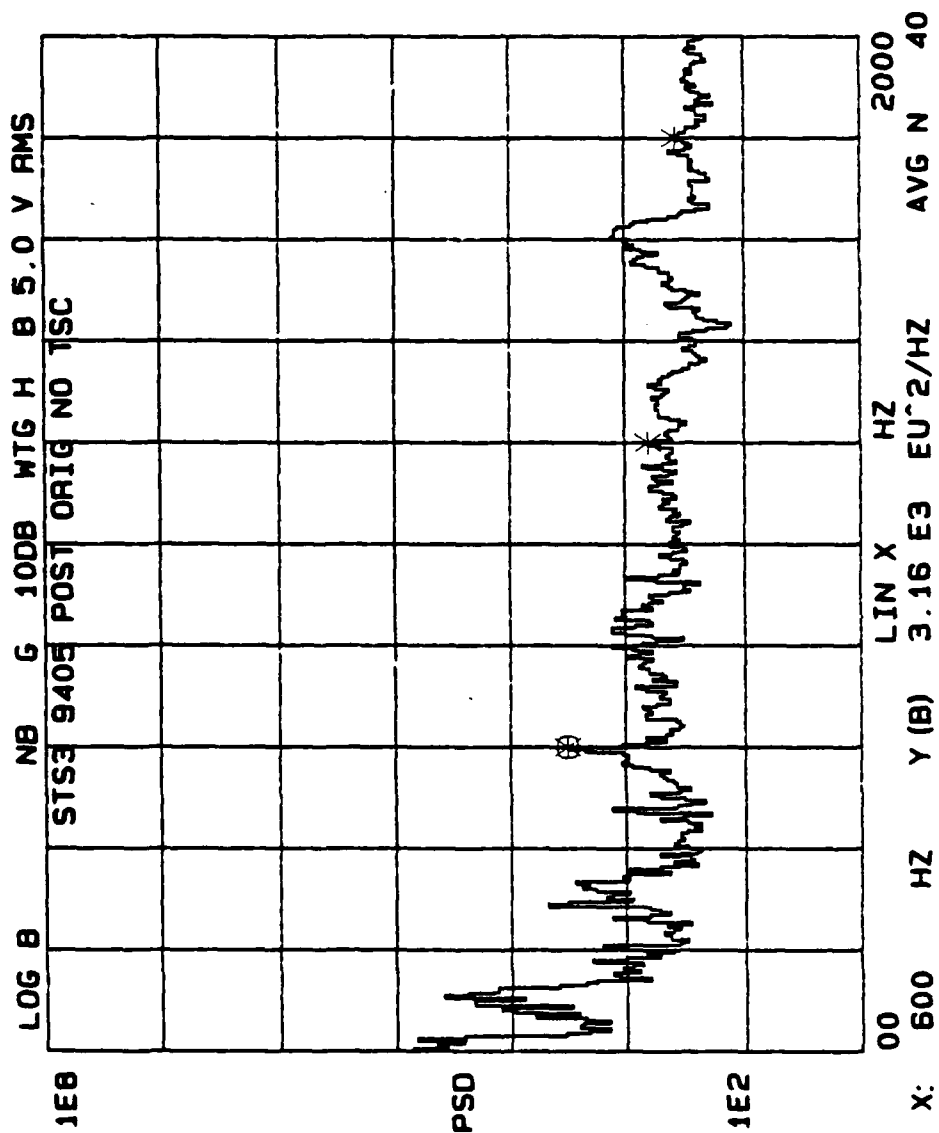
NSI-SML FORM 147 (MAY. 79)

NASA-JSC

125

130

STS2 9403 PRE ORIG

LOG B

1E8

PSO

1E2

X: 00   HZ   Y(B)   LIN X   HZ
      600   1.48 E1   EU^2/HZ   AVG N   40
                                          2000

```
          ALFA1=A1                                                        ABP01660
          ALFA2=1./A1                                                     ABP0161͡ ͡
          BETA1=D/E                                                       ABP016ι
          BETA2=1./(D*E)                                                  ABP01690
          GAMMA1=D**2.                                                    ABP01700
          GAMMA2=1./D**2.                                                 ABP01710
          NUM1(1)=ALFA1*(WODIG**2.)                                       ABP01720
          NUM1(2)=0.                                                      ABP01730
          NUM1(3)=1.                                                      ABP01740
          DEN1(1)=GAMMA1*(WODIG**2.)                                      ABP01750
          DEN1(2)=BETA1*WODIG                                             ABP01760
          DEN1(3)=1.                                                      ABP01770
          NUM2(1)=ALFA2*(WODIG**2.)                                       ABP01780
          NUM2(2)=0.                                                      ABP01790
          NUM2(3)=1.                                                      ABP01800
          DEN2(1)=GAMMA2*(WODIG**2.)                                      ABP01810
          DEN2(2)=BETA2*WODIG                                             ABP01820
   .      DEN2(3)=1.                                                      ABP01830
          RHO=RHO1*RHO2                                                   ABP01840
          INUM1=3                                                         ABP01850
          INUM2=3                                                         ABP01860
          IDEN1=3                                                         ABP01870
          IDEN2=3                                                         ABP01880
          CALL PMPY(ANUM,IANUM,NUM1,INUM1,NUM2,INUM2)                     ABP01890
          CALL PMPY(ADEN,IADEN,DEN1,IDEN1,DEN2,IDEN2)                     ABP01900
          WRITE(4,110)RHO                                                 ABP01910
          WRITE(4,120)ANUM(5),ANUM(4),ANUM(3),ANUM(2),ANUM(1)            ABP01920
          DO 105 I=1,5                                                    ABP01930
             ANUM(I)=ANUM(I)*RHO                                          ABP01940
  105 CONTINUE                                                            ABP01950
          WRITE(4,130)ANUM(5),ANUM(4),ANUM(3),ANUM(2),ANUM(1)            ABP01960
          DO 106 I=1,5                                                    ABP01970
             ANUM(I)=ANUM(I)/RHO                                          ABP01980
  106 CONTINUE                                                            ABP01990
          WRITE(4,140)ADEN(5),ADEN(4),ADEN(3),ADEN(2),ADEN(1)            ABP02000
  110 FORMAT('1','SECTION 2 OUTPUT',//,                                   ABP02010
         &' ANALOG ELLIPTIC BANDPASS FILTER TRANSFER FUNCTION'           ABP02020
         &,//,' NUMERATOR COEFFICIENT = RHO = ',F9.6,/)                  ABP02030
  120 FORMAT(' NUMERATOR POLYNOMIAL (NORMALIZED)'                         ABP02040
         &,/,E12.5,' S**4 +',/,E12.5,' S**3 +'                           ABP02050
         &,/,E12.5,' S**2 +',/,E12.5,' S     +',/,E12.5,//)              ABP02060
  130 FORMAT(' NUMERATOR POLYNOMIAL (UN-NORMALIZED)'                      ABP02070
         &,/,E12.5,' S**4 +',/,E12.5,' S**3 +'                           ABP02080
         &,/,E12.5,' S**2 +',/,E12.5,' S     +',/,E12.5,//)              ABP02090
  140 FORMAT(' DENOMINATOR POLYNOMIAL (NORMALIZED)'                       ABP02100
         &,/,E12.5,' S**4 +',/,E12.5,                                    ABP02110
         &' S**3 +',/,E12.5,' S**2 +',/,E12.5,' S     +',/,E12.5,///)    ABP02120
C***************************************************************************ABP02130
C                                                                        *ABP02140
C                           SECTION 2A                                   *ABP02150
C                                                                        *ABP02160
C    CALCULATE THE COMPLEX POLES AND ZEROS OF THE ANALOG FILTER          *ABP02170
C                                                                        *ABP02180
C***************************************************************************ABP02190
          IPDEG = 4                                                      ABP02200
```

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C     CHOOSE R17=R27=1./(WO*C1)(APPROX)=26.5 KOHMS              *ABP01110
C     USE MEASURED VALUES FOR CALCULATIONS                     *ABP01120
C                                                              *ABP01130
C*****************************************************************ABP01140
      C11=.00996E-06                                            ABP01150
      C12=.00995E-06                                            ABP01160
      C21=.01030E-06                                            ABP01170
      C22=.01034E-06                                            ABP01180
      R17=26.7E+03                                              ABP01190
      R27=26.7E+03                                              ABP01200
C*****************************************************************ABP01210
C     ELLIPTIC BANDPASS FILTER STAGE RESISTOR VALUES            ABP01220
C*****************************************************************ABP01230
      R11=(E/(K*D*WO*C11))*SQRT(A/C)                            ABP01240
      R12=K*R11*SQRT(C/A)                                       ABP01250
      R13=1./(D*WO*C11)                                         ABP01260
      R14=(R17/K)*SQRT(A/C)                                     ABP01270
   .  R15=(D/(K*A1*WO*C12))*SQRT(A/C)                           ABP01280
      R16=C11*R13/C12                                           ABP01290
      WRITE(4,20)C11,C12,R17,R11,R12,R13,R14,R15,R16            ABP01300
      R21=((D*E)/(K*WO*C21))*SQRT(A/C)                          ABP01310
      R22=(K*R21)*SQRT(C/A)                                     ABP01320
      R23=D/(WO*C21)                                            ABP01330
      R24=(R27/K)*SQRT(A/C)                                     ABP01340
      R25=(A1/(K*D*WO*C22))*SQRT(A/C)                           ABP01350
      R26=C21*R23/C22                                           ABP01360
      WRITE(4,30)C21,C22,R27,R21,R22,R23,R24,R25,R26            ABP01370
   10 FORMAT(' SECTION 1 OUTPUT',//,                            ABP01380
     &' INPUT AND DERIVED PARAMETERS FOR FURTHER CALCULATIONS'  ABP01390
     &,//,' A = ',F9.6,/,' B = ',F9.6,/,' C = ',F9.6,/,' D = ', ABP01400
     &F9.6,/,' E = ',F9.6,/,' A1 = ',F9.6,/,' FO = ',F9.3,/,' WO = ' ABP01410
     &,F9.3,/,' Q = ',F9.6,/,' K = ',F9.6,/,' K1 = ',F9.6,/,    ABP01420
     &' K2 ',F9.6,/,' WO(DIG) = ',F9.3,/,' FO(DIG) = ',F9.3,///) ABP01430
   20 FORMAT(' ELLIPTIC ANALOG BPF COMPONENT VALUES',//,' FIRST STAGE' ABP01440
     &,//,' C11 = ',E8.3,/,' C12 = ',E8.3,/,' R17 = ',E8.3,     ABP01450
     &/,' R11 = ',E8.3,/,' R12 = ',E8.3,/,' R13 = ',E8.3,/,     ABP01460
     &' R14 = ',E8.3,/,' R15 = ',E8.3,/,' R16 = ',E8.3,//)      ABP01470
   30 FORMAT(' SECOND STAGE',//,                                ABP01480
     &' C21 = ',E8.3,/,' C22 = ',E8.3,/,' R27 = ',E8.3,         ABP01490
     &/,' R21 = ',E8.3,/,' R22 = ',E8.3,/,' R23 = ',E8.3,/,     ABP01500
     &' R24 = ',E8.3,/,' R25 = ',E8.3,/,' R26 = ',E8.3)         ABP01510
C*****************************************************************ABP01520
C                                                              *ABP01530
C                          SECTION 2                           *ABP01540
C                                                              *ABP01550
C     IN THIS PORTION OF THE PROGRAM WE COMPUTE THE ANALOG TRANSFER *ABP01560
C     FUNCTION OF THE ELLIPTIC PAND PASS FILTER.  IF THE ANALOG *ABP01570
C     FUNCTION ALONE IS DESIRED THEN WE USE WO FOR CALCULATIONS. *ABP01580
C     IF THE ANALOG TRANSFER FUNCTION IS DESIRED FOR DIGITAL   *ABP01590
C     TRANSFORMATION THEN WE MUST USE THE PRE-WARPED ANALOG TO WO *ABP01600
C     WHICH IS WODIG.                                           ABP01610
C                                                              *ABP01620
C*****************************************************************ABP01630
      RHO1=K1*SQRT(C/A)                                         ABP01640
      RHO2=K2*SQRT(C/A)                                         ABP01650
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          COMPLEX AZERO(4),APOLE(4)                                   ABP00560
C SECTION 3                                                           ABP00570
          INTEGER IZM,IZP,IDNUM,IDDEN,IDTMP                           ABP00580
          REAL TNCOEF,TDCOEF                                          ABP00590
          REAL ZM1(5),ZM2(5),ZM3(5),ZM4(5),ZP1(5),ZP2(5),ZP3(5),ZP4(5) ABP00600
          REAL DNUM(5),DDEN(5),DTMP(9)                                ABP00610
C SECTION 3A                                                          ABP00620
          REAL DNMINV(5),DDNINV(5)                                    ABP00630
          REAL RZ(4),RP(4)                                            ABP00640
          COMPLEX DZERO(4),DPOLE(4)                                   ABP00650
C SECTION 4                                                           ABP00660
          INTEGER I4,I2                                               ABP00670
          COMPLEX*16 DZ4(4),DP4(4),DZ21(2),DP21(2),DZ22(2),DP22(2)    ABP00680
          COMPLEX*16 DN4(4),DD4(4),DN21(2),DD21(2),DN22(2),DD22(2)    ABP00690
          COMPLEX DN45(5),DD45(5),DN213(3),DD213(3),DN223(3),DD223(3) ABP00700
C*************************************************************************ABP00710
C     TABULATED INPUT PARAMETERS FOR DESIRED SECOND ORDER LOWPASS     ABP00720
C  -  FILTER EQUIVALENT HAVING THE FOLLOWING CHARACTERISTICS:         ABP00730
C             N = 2                                                   ABP00740
C             MAXIMUM PASSBAND RIPPLE WIDTH (PRW) = 2.0 DB            ABP00750
C             MINIMUM LOSS IN THE STOPBAND (MSL) = 30.0 DB            ABP00760
C             NORMALIZED TRANSITION WIDTH = 2.2921                    ABP00770
C             FILTER GAIN (K) = 1.0                                   ABP00780
C*************************************************************************ABP00790
          F0=600.                                                     ABP00800
          A=21.164003                                                 ABP00810
          B=0.787152                                                  ABP00820
          C=0.842554                                                  ABP00830
          Q=12.                                                       ABP00840
          PI=3.1415927                                                ABP00850
          K=1.                                                        ABP00860
C*************************************************************************ABP00870
C     DERIVED PARAMETERS                                              ABP00880
C*************************************************************************ABP00890
          E=(1./B)*SQRT((C+4.*Q**2.+SQRT((C+4.*Q**2.)**2.-(2.*B*Q)**2.))/2.)ABP00900
          D=.5*((B*E/Q)+SQRT((B*E/Q)**2.-4.))                         ABP00910
          A1=1.+(1./(2.*Q**2.))*(A+SQRT(A**2.+4.*A*Q**2.))            ABP00920
          K1=SQRT(K)                                                  ABP00930
          K2=K1                                                       ABP00940
          T=4.*192./6.666E+06                                         ABP00950
          TDIV2=T/2.                                                  ABP00960
          W0=2.*PI*F0                                                 ABP00970
          WODIG=(1./TDIV2)*ATAN(W0*TDIV2)                             ABP00980
          FODIG=WODIG/(2.*PI)                                         ABP00990
          WRITE(4,10)A,B,C,D,E,A1,F0,W0,Q,K,K1,K2,WODIG,FODIG         ABP01000
C*************************************************************************ABP01010
C                                                                     *ABP01020
C                          SECTION 1                                  *ABP01030
C                                                                     *ABP01040
C     THIS PROGRAM SECTION COMPUTES ANALOG ELLIPTIC BANDPASS FILTER   *ABP01050
C     RESISTOR AND CAPACITOR VALUES USING THE ABSOLUTE AND DERIVED    *ABP01060
C     PARAMETERS CALCULATED ABOVE:                                    *ABP01070
C                                                                     *ABP01080
C     CHOOSE C11=C21=.01E-06 (APPROX)=.01 UF                          *ABP01090
C     CHOOSE C12=C22=.01E-06(APPROX)=.01 UF                           *ABP01100
```

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C****************************************************************ABP00010
C                                                              *ABP00020
C                         APPENDIX C                           *ABP00030
C                                                              *ABP00040
C           FORTRAN PROGRAM ABPDBP AND PROGRAM OUTPUT          *ABP00050
C                                                              *ABP00060
C                                                              *ABP00070
C      THIS PROGRAM CALCULATES:                                *ABP00080
C                                                              *ABP00090
C      1)   ANALOG ELLIPTIC BANDPASS FILTER RESISTOR AND CAPACITOR  *ABP00100
C           VALUES (STARTING FROM TABULATED PARAMETERS CORRESPONDING  *ABP00110
C           TO THE DESIRED FILTER RESPONSE)                   *ABP00120
C                                                              *ABP00130
C      2)   ANALOG ELLIPTIC BANDPASS TRANSFER FUNCTION (IF DESIRED FOR  *ABP00140
C           DIGITAL TRANSFORMATION THEN MUST MODIFY CODE IN THIS PROGRAM  *ABP00150
C           SECTION AND SUBSTITUTE WODIG FOR WO TO REALIZE NECESSARY  *ABP00160
C           PRE-WARPING COMPENSATION)                         *ABP00170
C   .                                                          *ABP00180
C           A)   ANALOG TRANSFER FUNCTION COMPLEX ZEROS AND POLES  *ABP00190
C                                                              *ABP00200
C      3)   DIGITAL TRANSFER FUNCTION (BY APPLICATION OF THE BILINEAR  *ABP00210
C           TRANSFORM TO THE PRE-WARPED CASE OF THE ANALOG TRANSFER  *ABP00220
C           FUNCTION, WHICH IS PROVIDED IN SECTION 2 BY USING THE  *ABP00230
C           PRE-WARPED FREQUENCY ANALOG -- WODIG (VICE WO) -- IN THE  *ABP00240
C           ANALOG TRANSFER FUNCTION COMPUTATION).  THE BILINEAR  *ABP00250
C           TRANSFORM IS ACCOMPLISHED BY THE FOLLOWING SUBSTITUTION:  *ABP00260
C                                                              *ABP00270
C                             Z - 1                            *ABP00280
C                  S = (2/T) -------                           *ABP00290
C                             Z + 1                            *ABP00300
C                                                              *ABP00310
C           WHERE T IS THE SAMPLING FREQUENCY OF THE DIGITAL SYSTEM.  *ABP00320
C                                                              *ABP00330
C           A)   DIGITAL TRANSFER FUNCTION COMPLEX ZEROS AND POLES  *ABP00340
C                                                              *ABP00350
C      4)   POLYNOMIAL COEFFICIENTS FOR FIRST AND SECOND ORDER CASCADED  *ABP00360
C           TERMS WHICH WILL BE USED TO PERFORM A 2920 ANALOG/DIGITAL  *ABP00370
C           SIGNAL PROCESSING SIMULATION                      *ABP00380
C                                                              *ABP00390
C****************************************************************ABP00400
C     TYPE DECLARATIONS                                         ABP00410
C****************************************************************ABP00420
C SECTION 1                                                     ABP00430
      REAL A,B,C,D,E,A1,Q,K,K1,K2,WO,PI,FO,WODIG,FODIG,T,TDIV2   ABP00440
      REAL C11,C12,C21,C22                                      ABP00450
      REAL R11,R12,R13,R14,R15,R16,R17                          ABP00460
      REAL R21,R22,R23,R24,R25,R26,R27                          ABP00470
C SECTION 2                                                     ABP00480
      INTEGER INUM1,INUM2,IDEN1,IDEN2,IANUM,IADEN               ABP00490
      REAL RHO,RHO1,RHO2,ALFA1,ALFA2,BETA1,BETA2,GAMMA1,GAMMA2  ABP00500
      REAL NUM1(3),NUM2(3),DEN1(3),DEN2(3)                      ABP00510
      REAL ANUM(5),ADEN(5)                                      ABP00520
C SECTION 2A                                                    ABP00530
      INTEGER IERR,IPDEG                                        ABP00540
      REAL ANMINV(5),ADNINV(5)                                  ABP00550
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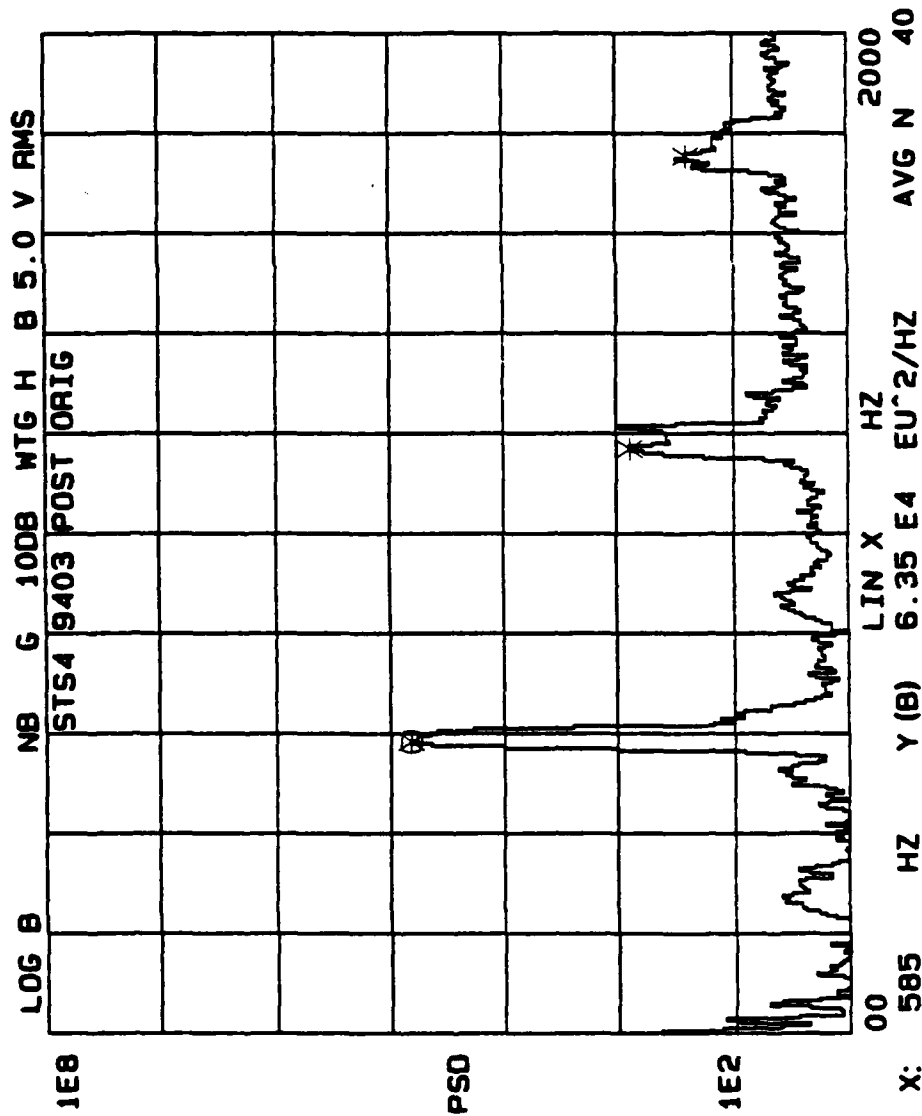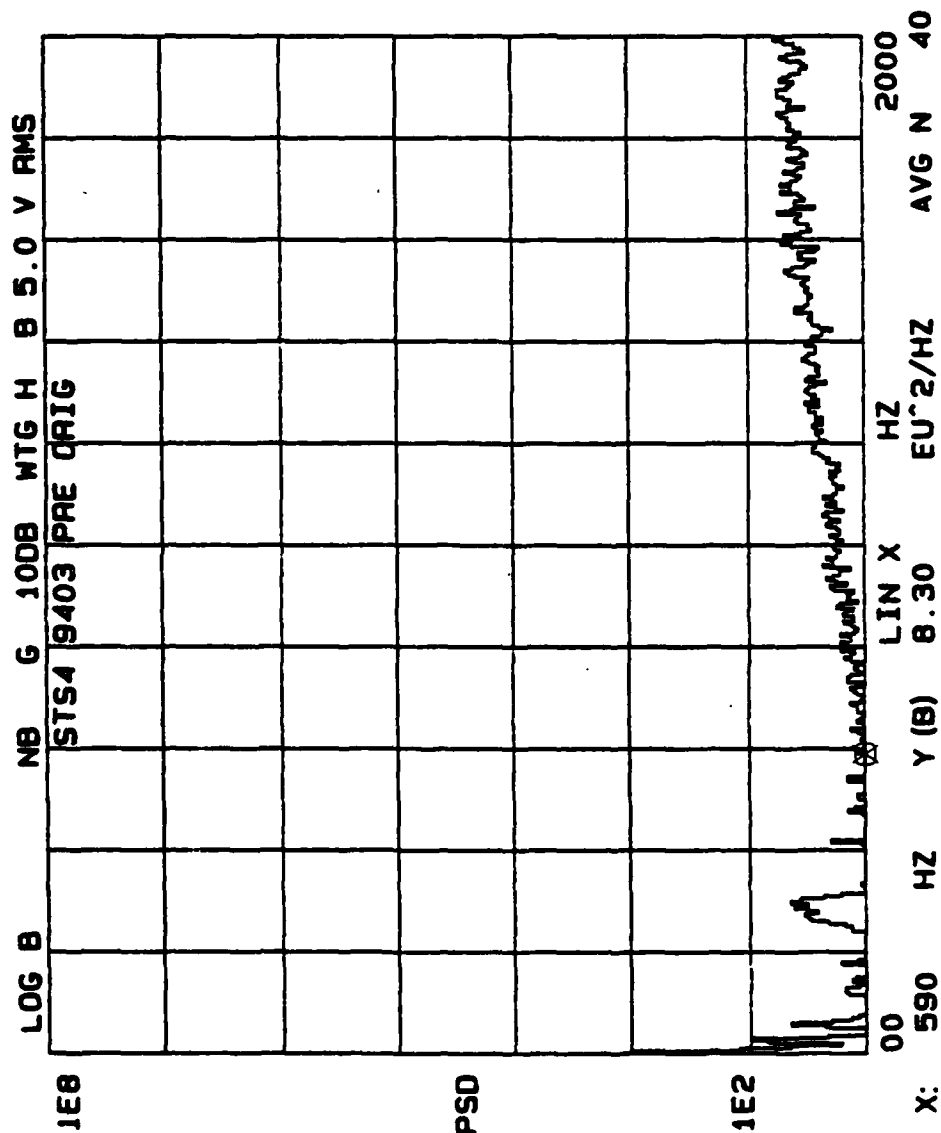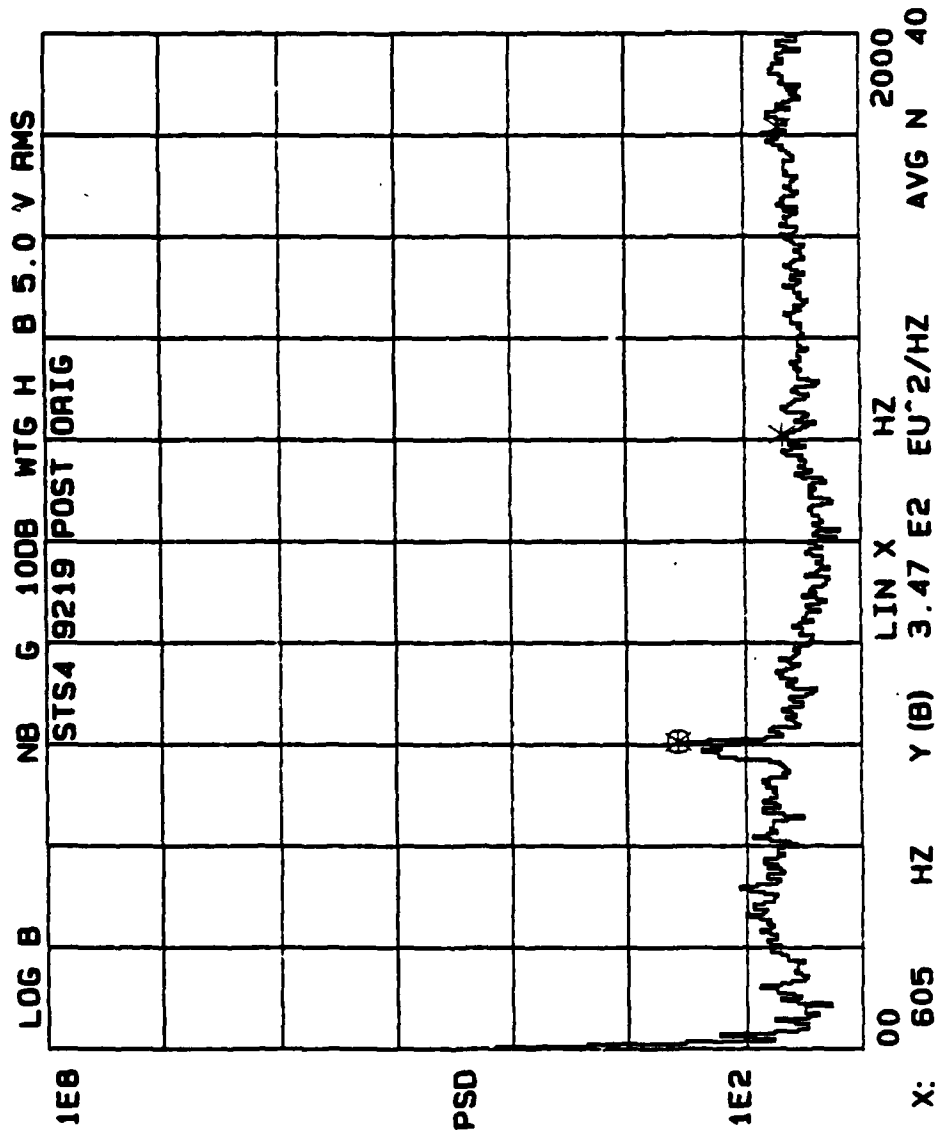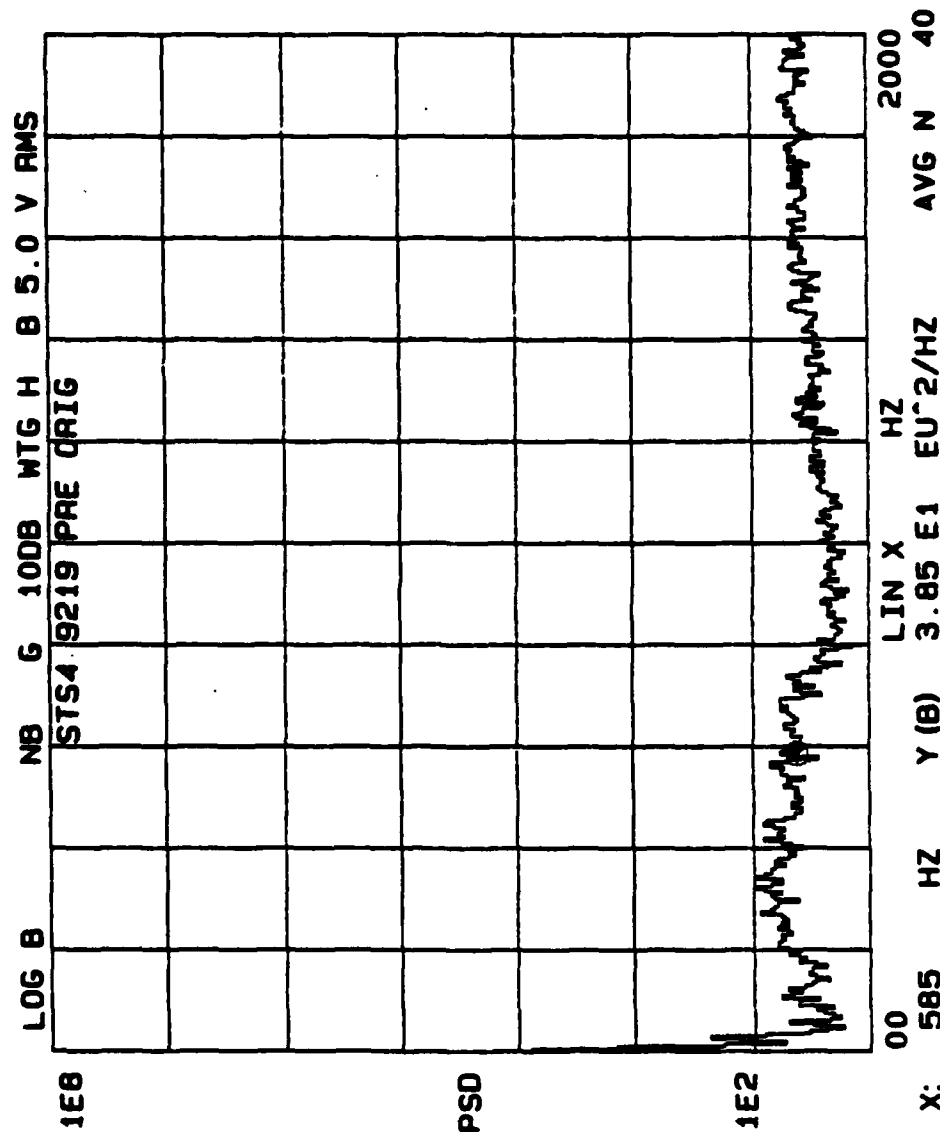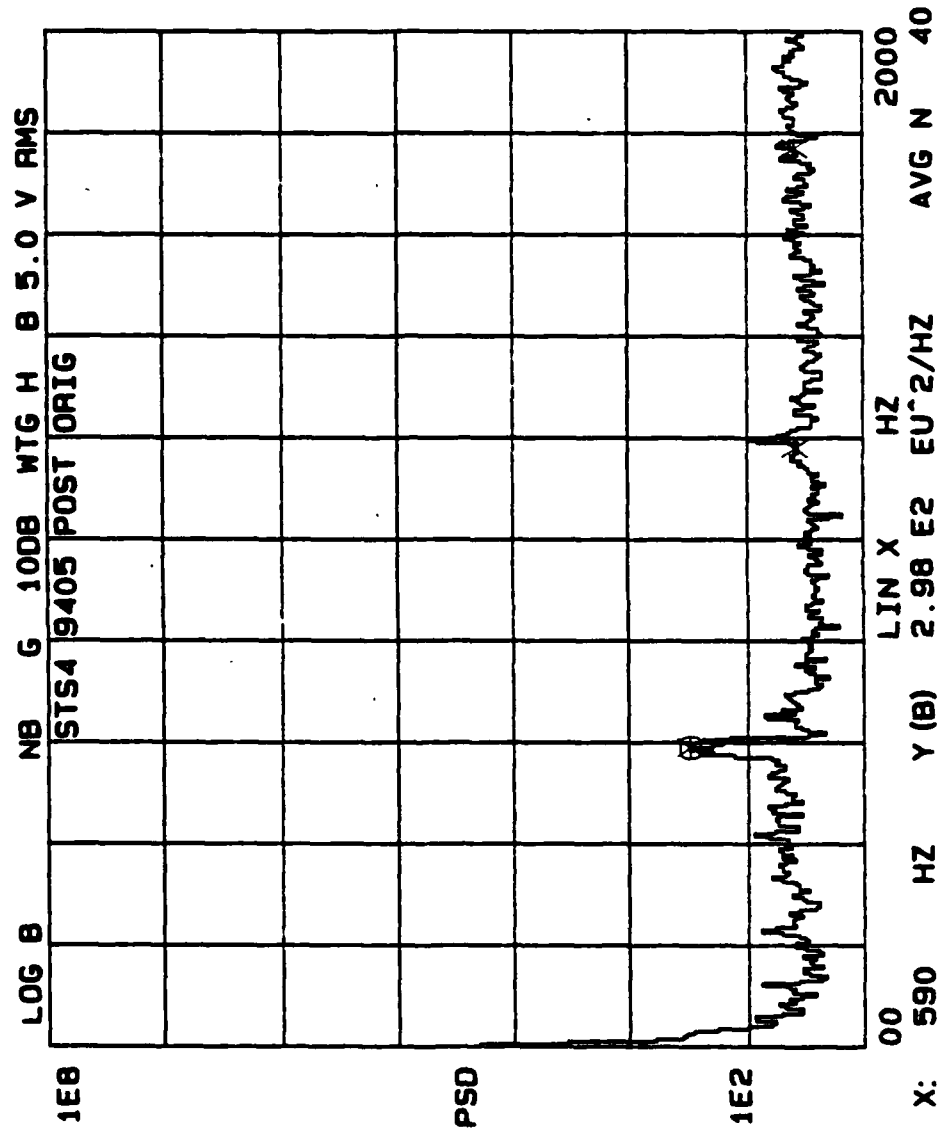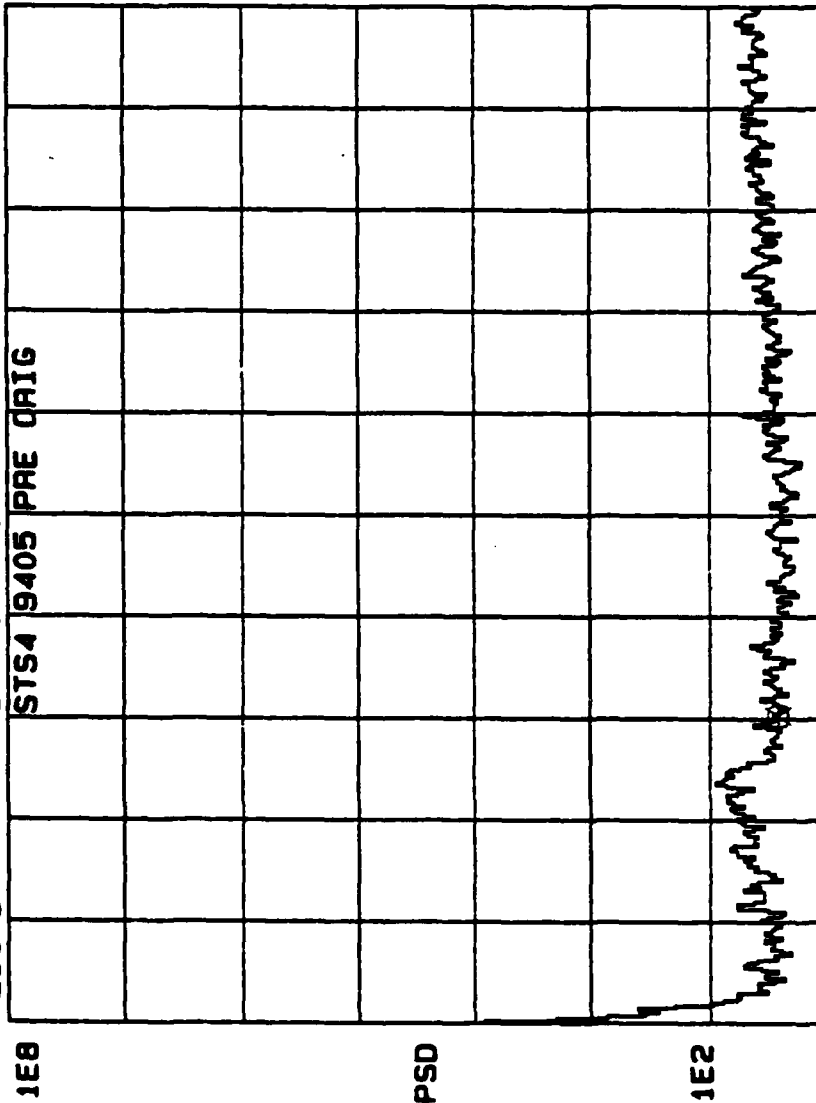
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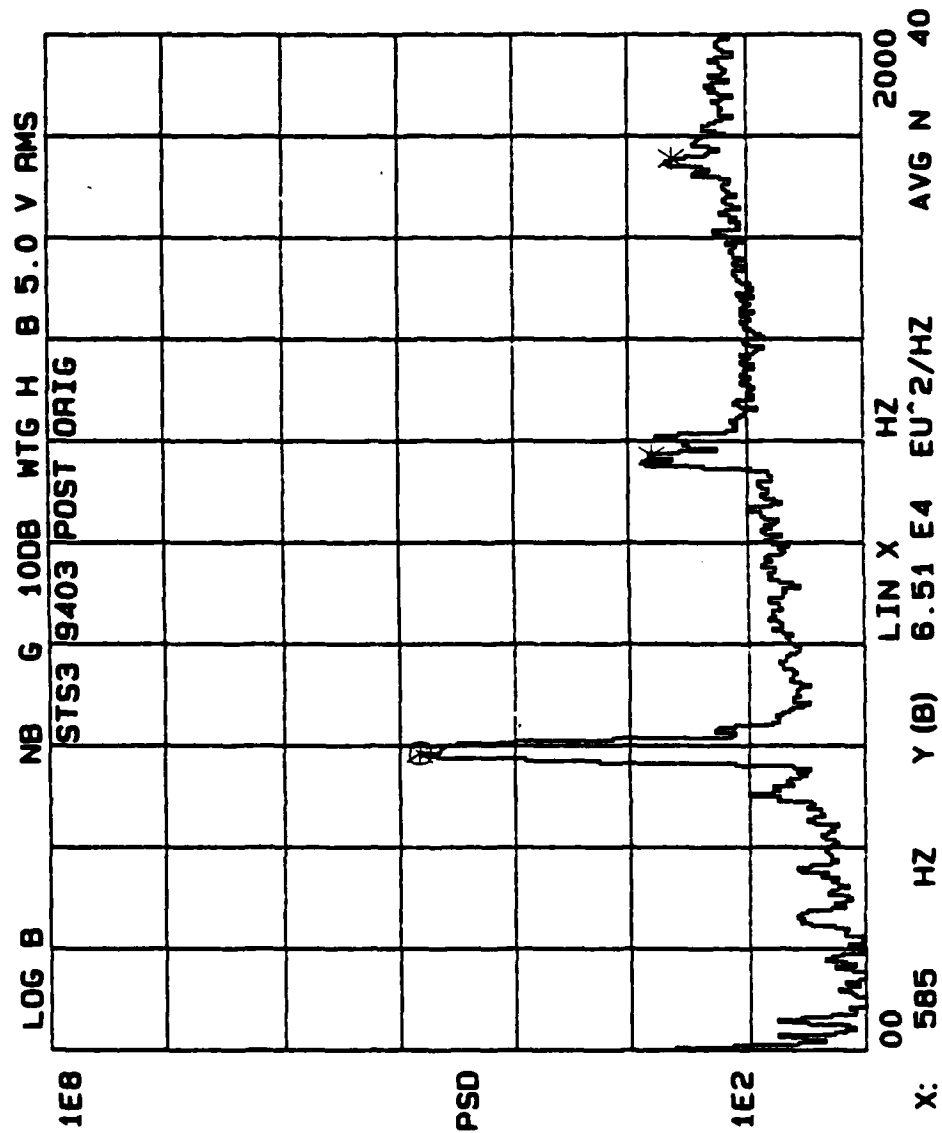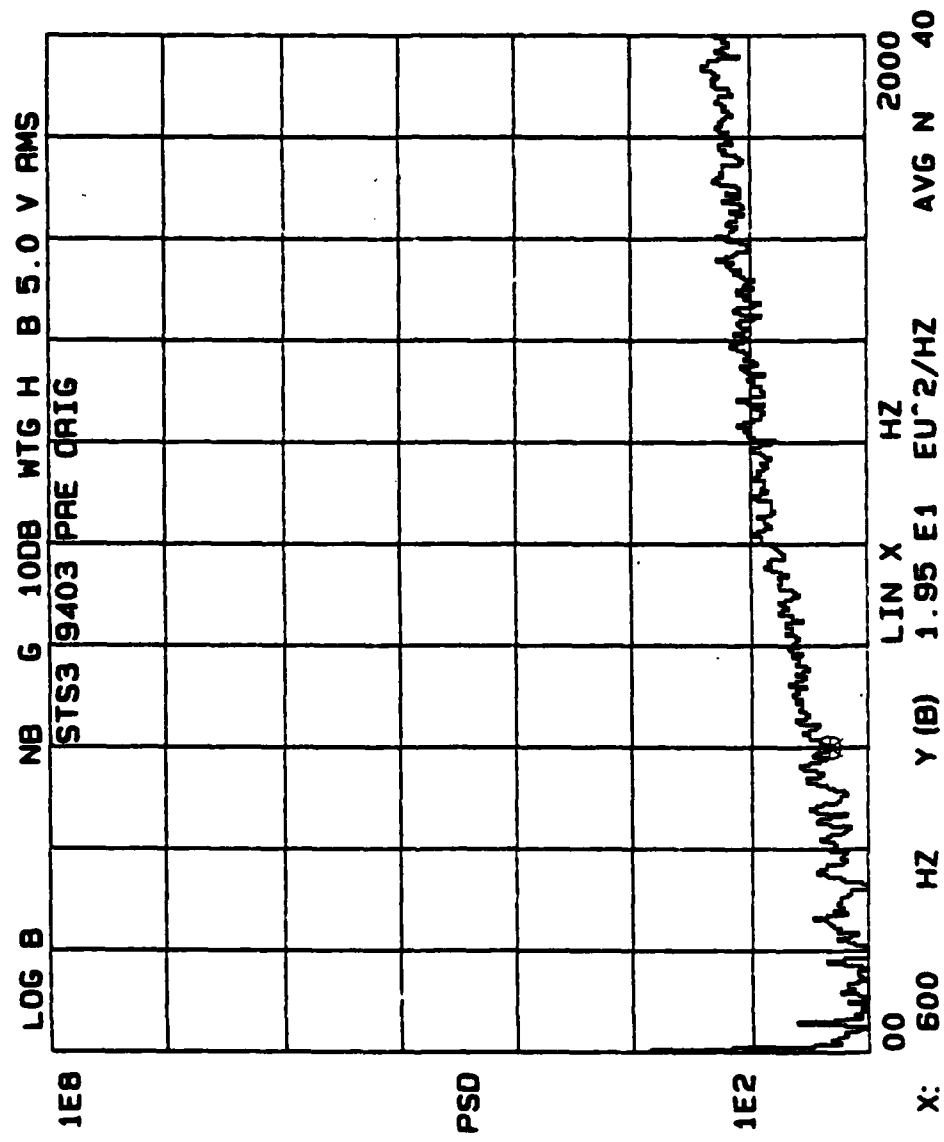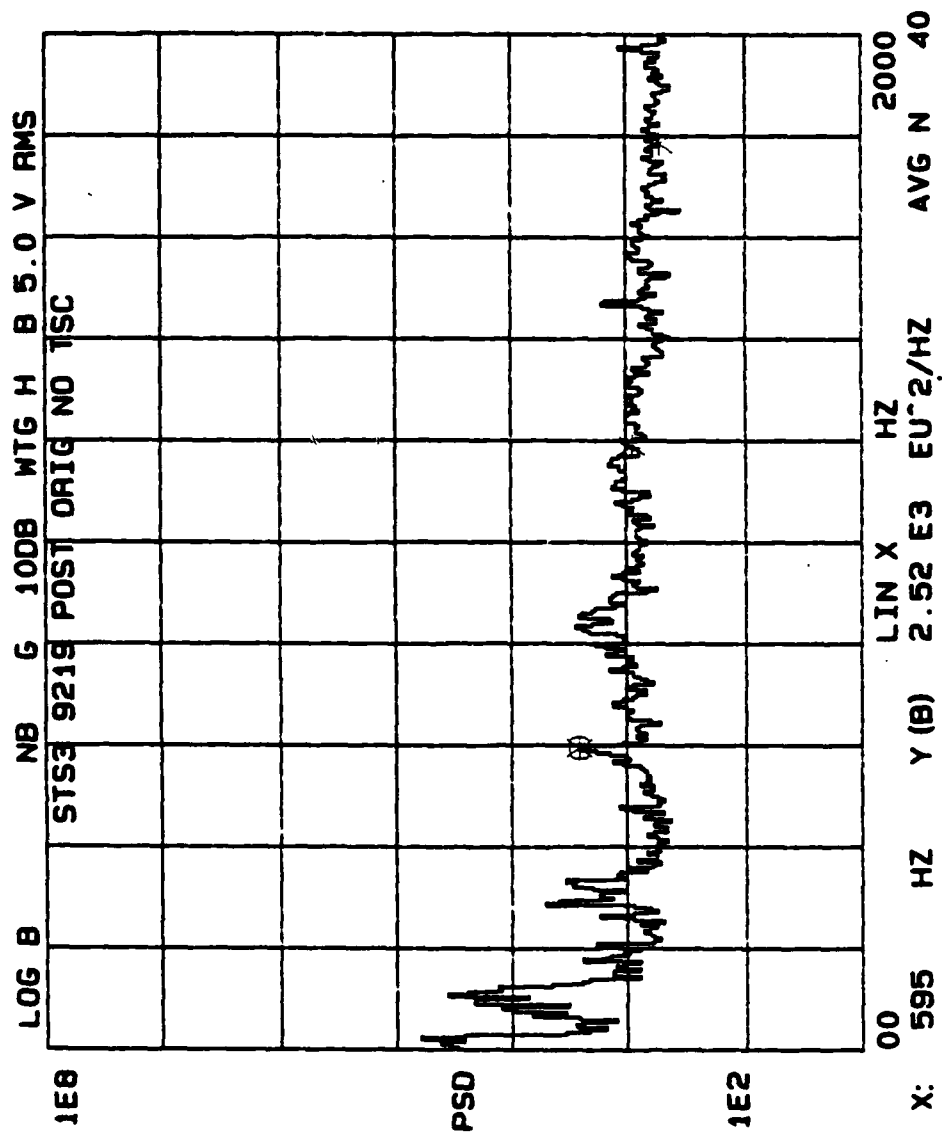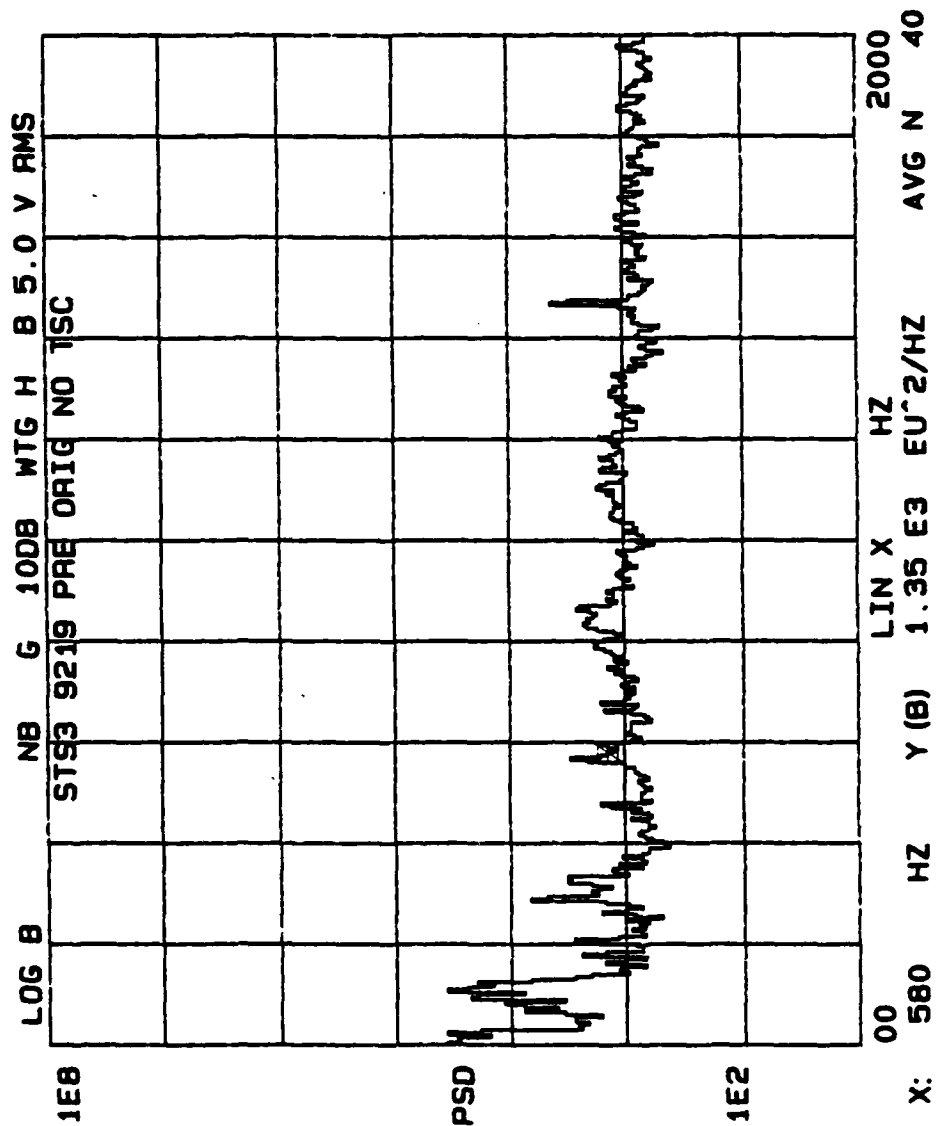
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      DO 1400 I=1,5                                                ABP02210
         ANMINV(I)=ANUM(6-I)                                       ABP02220
         ADNINV(I)=ADEN(6-I)                                       ABP02230
 1400 CONTINUE                                                     ABP02240
      CALL ZRPOLY(ANMINV,IPDEG,AZERO,IERR)                         ABP02250
      CALL ZRPOLY(ADNINV,IPDEG,APOLE,IERR)                         ABP02260
      WRITE(4,1410)                                                ABP02270
      WRITE(4,1420)AZERO(1),AZERO(2),AZERO(3),AZERO(4)             ABP02280
      WRITE(4,1430)APOLE(1),APOLE(2),APOLE(3),APOLE(4)             ABP02290
 1410 FORMAT(///,' SECTION 2A OUTPUT',//,                          ABP02300
     &' ANALOG FILTER COMPLEX POLES AND ZEROS',/)                  ABP02310
 1420 FORMAT(' ANALOG FILTER ZEROS',/,4(1X,E12.5,2X,E12.5,/),/)    ABP02320
 1430 FORMAT(' ANALOG FILTER POLES',/,4(1X,E12.5,2X,E12.5,/),///)  ABP02330
C**********************************************************************ABP02340
C                                                                  *ABP02350
C                           SECTION 3                              *ABP02360
C                                                                  *ABP02370
C  .  THE FOLLOWING STATEMENTS PERFORM THE BILINEAR TRANSFORMATION *ABP02380
C     OF THE ANALOG BANDPASS TRANSFER FUNCTION COMPUTED ABOVE IN   *ABP02390
C     SECTION 2                                                    *ABP02400
C                                                                  *ABP02410
C**********************************************************************ABP02420
      IZM=5                                                        ABP02430
      IZP=5                                                        ABP02440
      IDNUM=5                                                      ABP02450
      IDDEN=5                                                      ABP02460
      ZM1(1)=-1.                                                   ABP02470
      ZM1(2)=1.                                                    ABP02480
      ZM1(3)=0.                                                    ABP02490
      ZM1(4)=0.                                                    ABP02500
      ZM1(5)=0.                                                    ABP02510
      ZM2(1)=1.                                                    ABP02520
      ZM2(2)=-2.                                                   ABP02530
      ZM2(3)=1.                                                    ABP02540
      ZM2(4)=0.                                                    ABP02550
      ZM2(5)=0.                                                    ABP02560
      ZM3(1)=-1.                                                   ABP02570
      ZM3(2)=3.                                                    ABP02580
      ZM3(3)=-3.                                                   ABP02590
      ZM3(4)=1.                                                    ABP02600
      ZM3(5)=0.                                                    ABP02610
      ZM4(1)=1.                                                    ABP02620
      ZM4(2)=-4.                                                   ABP02630
      ZM4(3)=6.                                                    ABP02640
      ZM4(4)=-4.                                                   ABP02650
      ZM4(5)=1.                                                    ABP02660
      ZP1(1)=1.                                                    ABP02670
      ZP1(2)=1.                                                    ABP02680
      ZP1(3)=0.                                                    ABP02690
      ZP1(4)=0.                                                    ABP02700
      ZP1(5)=0.                                                    ABP02710
      ZP2(1)=1.                                                    ABP02720
      ZP2(2)=2.                                                    ABP02730
      ZP2(3)=1.                                                    ABP02740
      ZP2(4)=0.                                                    ABP02750
```

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          ZP2(5)=0.                                              ABP02760
          ZP3(1)=1.                                              ABP02770
          ZP3(2)=3.                                              ABP02780
          ZP3(3)=3.                                              ABP02790
          ZP3(4)=1.                                              ABP02800
          ZP3(5)=0.                                              ABP02810
          ZP4(1)=1.                                              ABP02820
          ZP4(2)=4.                                              ABP02830
          ZP4(3)=6.                                              ABP02840
          ZP4(4)=4.                                              ABP02850
          ZP4(5)=1.                                              ABP02860
          TNCOEF=ANUM(1)*(TDIV2**4.)                             ABP02870
          TDCOEF=ADEN(1)*(TDIV2**4.)                             ABP02880
          DO 200 I=1,5                                           ABP02890
             DNUM(I)=ZP4(I)*TNCOEF                               ABP02900
             DDEN(I)=ZP4(I)*TDCOEF                               ABP02910
     200 CONTINUE                                                ABP02920
   .      TNCOEF=ANUM(2)*(TDIV2**3.)                             ABP02930
          TDCOEF=ADEN(2)*(TDIV2**3.)                             ABP02940
          DO 210 I=1,5                                           ABP02950
             CALL PMPY(DTMP,IDTMP,ZM1,IZM,ZP3,IZP)               ABP02960
             DNUM(I)=DNUM(I)+(DTMP(I)*TNCOEF)                    ABP02970
             DDEN(I)=DDEN(I)+(DTMP(I)*TDCOEF)                    ABP02980
     210 CONTINUE                                                ABP02990
          TNCOEF=ANUM(3)*(TDIV2**2.)                             ABP03000
          TDCOEF=ADEN(3)*(TDIV2**2.)                             ABP03010
          DO 220 I=1,5                                           ABP03020
             CALL PMPY(DTMP,IDTMP,ZM2,IZM,ZP2,IZP)               ABP03030
             DNUM(I)=DNUM(I)+(DTMP(I)*TNCOEF)                    ABP03040
             DDEN(I)=DDEN(I)+(DTMP(I)*TDCOEF)                    ABP03050
     220 CONTINUE                                                ABP03060
          TNCOEF=ANUM(4)*(TDIV2)                                 ABP03070
          TDCOEF=ADEN(4)*(TDIV2)                                 ABP03080
          DO 230 I=1,5                                           ABP03090
             CALL PMPY(DTMP,IDTMP,ZM3,IZM,ZP1,IZP)               ABP03100
             DNUM(I)=DNUM(I)+(DTMP(I)*TNCOEF)                    ABP03110
             DDEN(I)=DDEN(I)+(DTMP(I)*TDCOEF)                    ABP03120
     230 CONTINUE                                                ABP03130
          TNCOEF=ANUM(5)                                         ABP03140
          TDCOEF=ADEN(5)                                         ABP03150
          DO 240 I=1,5                                           ABP03160
             DNUM(I)=DNUM(I)+(ZM4(I)*TNCOEF)                     ABP03170
             DDEN(I)=DDEN(I)+(ZM4(I)*TDCOEF)                     ABP03180
     240 CONTINUE                                                ABP03190
          DO 250 I=1,5                                           ABP03200
             DNUM(I)=DNUM(I)/DDEN(5)                             ABP03210
             DDEN(I)=DDEN(I)/DDEN(5)                             ABP03220
     250 CONTINUE                                                ABP03230
          RHO=RHO*DNUM(5)                                        ABP03240
          DO 260 I=1,5                                           ABP03250
             DNUM(I)=DNUM(I)/DNUM(5)                             ABP03260
     260 CONTINUE                                                ABP03270
          WRITE(4,310)RHO                                        ABP03280
          WRITE(4,320)DNUM(5),DNUM(4),DNUM(3),DNUM(2),DNUM(1)    ABP03290
          DO 305 I=1,5                                           ABP03300
```

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           DNUM(I)=DNUM(I)*RHO                                      ABP03310
       305 CONTINUE                                                 ABP03320
           WRITE(4,330)DNUM(5),DNUM(4),DNUM(3),DNUM(2),DNUM(1)      ABP03330
           WRITE(4,340)DDEN(5),DDEN(4),DDEN(3),DDEN(2),DDEN(1)      ABP03340
       310 FORMAT('1','SECTION 3 OUTPUT',//,                        ABP03350
          &' EQUIVALENT DIGITAL FILTER TRANSFER FUNCTION',//,       ABP03360
          &' NUMERATOR COEFFICIENT = ',E12.5,/)                     ABP03370
       320 FORMAT(' NUMERATOR (NORMALIZED)'                         ABP03380
          &,/,1X,E12.5,' + ',/,1X,E12.5,' Z**-1 +',/,1X,E12.5,' Z**-2 +', ABP03390
          &/,1X,E12.5,' Z**-3 +',/,1X,E12.5,' Z**-4',//)           ABP03400
       330 FORMAT(' NUMERATOR (UN-NORMALIZED)'                      ABP03410
          &,/,1X,E12.5,' + ',/,1X,E12.5,' Z**-1 +',/,1X,E12.5,' Z**-2 +', ABP03420
          &/,1X,E12.5,' Z**-3 +',/,1X,E12.5,' Z**-4',//)           ABP03430
       340 FORMAT(' DENOMINATOR'                                    ABP03440
          &,/,1X,E12.5,' + ',/,1X,E12.5,' Z**-1 +',/,1X,E12.5,' Z**-2 +', ABP03450
          &/,1X,E12.5,' Z**-3 +',/,1X,E12.5,' Z**-4',////)         ABP03460
C*************************************************************************ABP03470
C  .                                                                *ABP03480
C                             SECTION 3A                            *ABP03490
C                                                                   *ABP03500
C  CALCULATE THE COMPLEX POLES AND ZEROS OF THE DIGITAL FILTER      *ABP03510
C  AND THE RADIUS OF THE COMPLEX POLE AND ZERO VECTORS RELATIVE     *ABP03520
C  TO THE UNIT CIRCLE.                                              *ABP03530
C                                                                   *ABP03540
C*************************************************************************ABP03550
           IPDEG = 4                                                ABP03560
           DO 400 I=1,5                                             ABP03570
              DNMINV(I)=DNUM(6-I)                                   ABP03580
              DDNINV(I)=DDEN(6-I)                                   ABP03590
       400 CONTINUE                                                 ABP03600
           CALL ZRPOLY(DNMINV,IPDEG,DZERO,IERR)                     ABP03610
           CALL ZRPOLY(DDNINV,IPDEG,DPOLE,IERR)                     ABP03620
           DO 404 I=1,4                                             ABP03630
              RZ(I)=SQRT((REAL(DZERO(I)))**2.+(AIMAG(DZERO(I)))**2.) ABP03640
              RP(I)=SQRT((REAL(DPOLE(I)))**2.+(AIMAG(DPOLE(I)))**2.) ABP03650
       404 CONTINUE                                                 ABP03660
           WRITE(4,410)                                             ABP03670
           WRITE(4,420)DZERO(1),RZ(1),DZERO(2),RZ(2),DZERO(3),RZ(3), ABP03680
          &DZERO(4),RZ(4)                                           ABP03690
           WRITE(4,430)DPOLE(1),RP(1),DPOLE(2),RP(2),DPOLE(3),RP(3), ABP03700
          &DPOLE(4),RP(4)                                           ABP03710
       410 FORMAT(' SECTION 3A OUTPUT',//,                          ABP03720
          &' DIGITAL FILTER COMPLEX POLES AND ZEROS AND RADIUS',//) ABP03730
       420 FORMAT(' ZERO LOCATIONS (REAL,IMAG) AND RADIUS',/,       ABP03740
          &4(E12.5,2X,E12.5,2X,E12.5,/),/)                         ABP03750
       430 FORMAT(' POLE LOCATIONS (REAL,IMAG) AND RADIUS',/,       ABP03760
          &4(E12.5,2X,E12.5,2X,E12.5,/),///)                       ABP03770
C*************************************************************************ABP03780
C                                                                   *ABP03790
C                             SECTION 4                             *ABP03800
C                                                                   *ABP03810
C  COMPUTE THE POLYNOMIAL COEFFICIENTS OF QUADRATIC FACTORS FOR     *ABP03820
C  THE POLES AND ZEROS PREVIOUSLY DETERMINED.                       *ABP03830
C                                                                   *ABP03840
C*************************************************************************ABP03850
```

```
        I4=4                                                       ABP03860
        I2=2                                                       ABP03870
        DO 500 I=1,4                                               ABP03880
           DZ4(I)=CMPLX(REAL(DZERO(I)),AIMAG(DZERO(I)))            ABP03890
           DP4(I)=CMPLX(REAL(DPOLE(I)),AIMAG(DPOLE(I)))            ABP03900
  500 CONTINUE                                                     ABP03910
        DO 502 I=1,2                                               ABP03920
           DZ21(I)=DZ4(I)                                          ABP03930
           DP21(I)=DP4(I)                                          ABP03940
  502 CONTINUE                                                     ABP03950
        DO 504 I=3,4,1                                             ABP03960
           DZ22(I-2)=DZ4(I)                                        ABP03970
           DP22(I-2)=DP4(I)                                        ABP03980
  504 CONTINUE                                                     ABP03990
        CALL MAKPOL(I4,DZ4,DN4)                                    ABP04000
        CALL MAKPOL(I4,DP4,DD4)                                    ABP04010
        DN45(5)=CMPLX(1.,0.)                                       ABP04020
      · DD45(5)=CMPLX(1.,0.)                                       ABP04030
        DO 512 I=1,4                                               ABP04040
           DN45(I)=DN4(I)                                          ABP04050
           DD45(I)=DD4(I)                                          ABP04060
  512 CONTINUE                                                     ABP04070
        WRITE(4,514)                                               ABP04080
  514 FORMAT('1','SECTION 4 OUTPUT',//,                           ABP04090
      &' REASSEMBLE COEFFICIENTS FROM POLES AND ZEROS',//)         ABP04100
        WRITE(4,515)                                               ABP04110
        WRITE(4,520)DN45(5),DN45(4),DN45(3),DN45(2),DN45(1)        ABP04120
        WRITE(4,530)DD45(5),DD45(4),DD45(3),DD45(2),DD45(1)        ABP04130
  515 FORMAT(/' SINGLE FOURTH ORDER TRANSFER FUNCTION COEFFICIENTS',//) ABP04140
  520 FORMAT(' FOURTH ORDER NUMERATOR COEFFICIENTS (NORMALIZED)',/, ABP04150
      &5(1X,E12.5,2X,E12.5,/))                                     ABP04160
  530 FORMAT(' FOURTH ORDER DENOMINATOR COEFFICIENTS (NORMALIZED)',/, ABP04170
      &5(1X,E12.5,2X,E12.5,/),//)                                  ABP04180
        CALL MAKPOL(I2,DZ21,DN21)                                  ABP04190
        CALL MAKPOL(I2,DP21,DD21)                                  ABP04200
        DN213(3)=CMPLX(1.,0.)                                      ABP04210
        DD213(3)=CMPLX(1.,0.)                                      ABP04220
        DO 612 I=1,2                                               ABP04230
           DN213(I)=DN21(I)                                        ABP04240
           DD213(I)=DD21(I)                                        ABP04250
  612 CONTINUE                                                     ABP04260
        WRITE(4,614)                                               ABP04270
  614 FORMAT(' CASCADED SECOND ORDER TRANSFER FUNCTION COEFFICIENTS',/) ABP04280
        WRITE(4,615)                                               ABP04290
        WRITE(4,620)DN213(3),DN213(2),DN213(1)                     ABP04300
        WRITE(4,630)DD213(3),DD213(2),DD213(1)                     ABP04310
  615 FORMAT(/' FIRST STAGE QUADRATIC FUNCTION COEFFICIENTS',/)    ABP04320
  620 FORMAT(' COMPLEX (REAL,IMAG) NUMERATOR COEFFICIENTS',/,      ABP04330
      &1X,E12.5,2X,E12.5,                                          ABP04340
      &'  Z**2 +',/,1X,E12.5,2X,E12.5,'   Z +',/,1X,E12.5,2X,E12.5,/) ABP04350
  630 FORMAT(' COMPLEX (REAL,IMAG) DENOMINATOR COEFFICIENTS',/,    ABP04360
      &1X,E12.5,2X,E12.5,                                          ABP04370
      &'  Z**2 +',/,1X,E12.5,2X,E12.5,'   Z +',/,1X,E12.5,2X,E12.5,/) ABP04380
        CALL MAKPOL(I2,DZ22,DN22)                                  ABP04390
        CALL MAKPOL(I2,DP22,DD22)                                  ABP04400
```

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          DN223(3)=CMPLX(1.,0.)                                         ABP04410
          DD223(3)=CMPLX(1.,0.)                                         ABP04420
          DO 712 I=1,2                                                  ABP04430
              DN223(I)=DN22(I)                                          ABP04440
              DD223(I)=DD22(I)                                          ABP04450
      712 CONTINUE                                                      ABP04460
          WRITE(4,715)                                                  ABP04470
          WRITE(4,720)DN223(3),DN223(2),DN223(1)                        ABP04480
          WRITE(4,730)DD223(3),DD223(2),DD223(1)                        ABP04490
      715 FORMAT(/' SECOND STAGE QUADRATIC FUNCTION COEFFICIENTS',//)   ABP04500
      720 FORMAT(' COMPLEX (REAL,IMAG) NUMERATOR COEFFICIENTS',/,       ABP04510
          &1X,E12.5,2X,E12.5,                                          ABP04520
          &'   Z**2 +',/,1X,E12.5,2X,E12.5,'   Z +',/,1X,E12.5,2X,E12.5,/) ABP04530
      730 FORMAT(' COMPLEX (REAL,IMAG) DENOMINATOR COEFFICIENTS',/,     ABP04540
          &1X,E12.5,2X,E12.5,                                          ABP04550
          &'   Z**2 +',/,1X,E12.5,2X,E12.5,'   Z +',/,1X,E12.5,2X,E12.5,/) ABP04560
          STOP                                                          ABP04570
          END                                                          ABP04580
    C                                                                   ABP04590
    C     ...................................................................ABP04600
    C                                                                   ABP04610
    C         SUBROUTINE PMPY                                           ABP04620
    C                                                                   ABP04630
    C         PURPOSE                                                   ABP04640
    C             MULTIPLY TWO POLYNOMIALS                              ABP04650
    C                                                                   ABP04660
    C         USAGE                                                     ABP04670
    C             CALL PMPY(Z,IDIMZ,X,IDIMX,Y,IDIMY)                    ABP04680
    C                                                                   ABP04690
    C         DESCRIPTION OF PARAMETERS                                 ABP04700
    C             Z      - VECTOR OF RESULTANT COEFFICIENTS, ORDERED FROM ABP04710
    C                      SMALLEST TO LARGEST POWER                    ABP04720
    C             IDIMZ - DIMENSION OF Z (CALCULATED)                   ABP04730
    C             X      - VECTOR OF COEFFICIENTS FOR FIRST POLYNOMIAL, ORDEREDABP04740
    C                      FROM SMALLEST TO LARGEST POWER               ABP04750
    C             IDIMX - DIMENSION OF X (DEGREE IS IDIMX-1)            ABP04760
    C             Y      - VECTOR OF COEFFICIENTS FOR SECOND POLYNOMIAL, ABP04770
    C                      ORDERED FROM SMALLEST TO LARGEST POWER       ABP04780
    C             IDIMY - DIMENSION OF Y (DEGREE IS IDIMY-1)            ABP04790
    C                                                                   ABP04800
    C         REMARKS                                                   ABP04810
    C             Z CANNOT BE IN THE SAME LOCATION AS X                 ABP04820
    C             Z CANNOT BE IN THE SAME LOCATION AS Y                 ABP04830
    C                                                                   ABP04840
    C         SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED             ABP04850
    C             NONE                                                  ABP04860
    C                                                                   ABP04870
    C         METHOD                                                    ABP04880
    C             DIMENSION OF Z IS CALCULATED AS IDIMX+IDIMY-1         ABP04890
    C             THE COEFFICIENTS OF Z ARE CALCULATED AS SUM OF PRODUCTS ABP04900
    C             OF COEFFICIENTS OF X AND Y , WHOSE EXPONENTS ADD UP TO THE ABP04910
    C             CORRESPONDING EXPONENT OF Z.                          ABP04920
    C                                                                   ABP04930
    C     ...................................................................ABP04940
    C                                                                   ABP04950
```

```
      SUBROUTINE PMPY(Z,IDIMZ,X,IDIMX,Y,IDIMY)                ABP04960
      DIMENSION Z(1),X(1),Y(1)                                ABP04970
C                                                             ABP04980
      IF(IDIMX*IDIMY)10,10,20                                 ABP04990
   10 IDIMZ=0                                                 ABP05000
      GO TO 50                                                ABP05010
   20 IDIMZ=IDIMX+IDIMY-1                                     ABP05020
      DO 30 I=1,IDIMZ                                         ABP05030
   30 Z(I)=0.                                                 ABP05040
      DO 40 I=1,IDIMX                                         ABP05050
      DO 40 J=1,IDIMY                                         ABP05060
      K=I+J-1                                                 ABP05070
   40 Z(K)=X(I)*Y(J)+Z(K)                                     ABP05080
   50 RETURN                                                  ABP05090
      END                                                     ABP05100
C                                                             ABP05110
C----------------------------------------------------------ABP05120
C  .                                                          ABP05130
C      SUBROUTINE MAKPOL                                      ABP05140
C                                                             ABP05150
C      PURPOSE                                                ABP05160
C         TO COMPUTE THE COMPLEX COEFFICIENTS OF AN N-TH DEGREE POLY-  ABP05170
C         NOMIAL GIVEN N COMPLEX ROOTS OF THE POLYNOMIAL     ABP05180
C                                                             ABP05190
C      USAGE                                                  ABP05200
C         CALL MAKPOL(N,R,C)                                  ABP05210
C                                                             ABP05220
C      DESCRIPTION OF PARAMETERS                              ABP05230
C         N - NUMBER OF ROOTS GIVEN AND DEGREE OF POLYNOMIAL.  THE    ABP05240
C             COEFFICIENT OF THE HIGHEST POWER OF THE UNKNOWN IS ALWAYS ABP05250
C             UNITY, AND IS NOT COMPUTED BY "MAKPOL".         ABP05260
C         R - DOUBLE PRECISION COMPLEX ARRAY CONTAINING THE COMPLEX   ABP05270
C             ROOTS                                           ABP05280
C         C - DOUBLE PRECISION COMPLEX ARRAY CONTAINING THE COMPLEX   ABP05290
C             COEFFICIENTS                                    ABP05300
C                                                             ABP05310
C      REMARKS                                                ABP05320
C         ARRAYS R AND C ARE TYPED COMPLEX*16                 ABP05330
C                                                             ABP05340
      SUBROUTINE MAKPOL(N,R,C)                                ABP05350
      COMPLEX*16 R(N),C(N)                                    ABP05360
      IF(N.LE.0) RETURN                                       ABP05370
      DO 10 I=1,N                                             ABP05380
   10 C(I)=R(I)                                               ABP05390
      K=N                                                     ABP05400
      M=N-1                                                   ABP05410
      DO 20 L=1,M                                             ABP05420
      DO 30 I=2,K                                             ABP05430
   30 C(I)=C(I)+C(I-1)                                        ABP05440
      K=K-1                                                   ABP05450
      DO 20 I=1,K                                             ABP05460
      J=I+L                                                   ABP05470
      C(I)=R(J)*C(I)                                          ABP05480
   20 CONTINUE                                                ABP05490
      K=N/2                                                   ABP05500
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      K=2*K/(N-K)
      DO 40 I=K,N,2                                    ABP05510
40 C(I)=-C(I)                                          ABP05520
      RETURN                                           ABP05530
      END                                              ABP05540
                                                       ABP05550
```

ABPDBP OUTPUT

SECTION 1 OUTPUT

INPUT AND DERIVED PARAMETERS FOR FURTHER CALCULATIONS

A = 21.164001
B = 0.787152
C = 0.842554
D = 1.035090
E = 30.507828
A1 = 1.463835
FO =   600.000
WO = 3769.911
Q = 12.000000
K = 1.000000
K1 = 1.000000
K2 1.000000
WO(DIG) = 3712.266
FO(DIG) =   590.825

ELLIPTIC ANALOG BPF COMPONENT VALUES

FIRST STAGE

C11 = .996E-08
C12 = .995E-08
R17 = .267E+05
R11 = .393E+07
R12 = .785E+06
R13 = .257E+05
R14 = .134E+06
R15 = .945E+05
R16 = .258E+05

SECOND STAGE

C21 = .103E-07
C22 = .103E-07
R27 = .267E+05
R21 = .408E+07
R22 = .813E+06
R23 = .267E+05
R24 = .134E+06
R25 = .182E+06
R26 = .266E+05

SECTION 2 OUTPUT

ANALOG ELLIPTIC BANDPASS FILTER TRANSFER FUNCTION

NUMERATOR COEFFICIENT = RHO = 0.039811

NUMERATOR POLYNOMIAL (NORMALIZED)
0.10000E+01 S**4 +
0.0   S**3 +
0.29587E+08 S**2 +
0.0   S   +
0.18991E+15

NUMERATOR POLYNOMIAL (UN-NORMALIZED)
0.39811E-01 S**4 +
0.0   S**3 +
0.11779E+07 S**2 +
0.0   S   +
0.75606E+13

DENOMINATOR POLYNOMIAL (NORMALIZED)
0.10000E+01 S**4 +
0.24351E+03 S**3 +
0.27642E+08 S**2 +
0.33558E+10 S   +
0.18991E+15

SECTION 2A OUTPUT

ANALOG FILTER COMPLEX POLES AND ZEROS

ANALOG FILTER ZEROS
-0.45776E-03   0.30683E+04
-0.45776E-03   -0.30683E+04
 0.45776E-03   0.44914E+04
 0.45776E-03   -0.44914E+04

ANALOG FILTER POLES
-0.58188E+02   0.35859E+04
-0.58188E+02   -0.35859E+04
-0.63567E+02   0.38421E+04
-0.63567E+02   -0.38421E+04

SECTION 3 OUTPUT

EQUIVALENT DIGITAL FILTER TRANSFER FUNCTION

NUMERATOR COEFFICIENT = 0.39516E-01

NUMERATOR (NORMALIZED)
 0.10000E+01 +
-0.36279E+01 Z**-1 +
 0.52861E+01 Z**-2 +
-0.36279E+01 Z**-3 +
 0.10000E+01 Z**-4

NUMERATOR (UN-NORMALIZED)
 0.39516E-01 +
-0.14336E+00 Z**-1 +
 0.20888E+00 Z**-2 +
-0.14336E+00 Z**-3 +
 0.39516E-01 Z**-4

DENOMINATOR
 0.10000E+01 +
-0.36251E+01 Z**-1 +
 0.52586E+01 Z**-2 +
-0.35768E+01 Z**-3 +
 0.97353E+00 Z**-4

SECTION 3A OUTPUT

DIGITAL FILTER.COMPLEX POLES AND ZEROS AND RADIUS

ZERO LOCATIONS (REAL,IMAG) AND RADIUS
0.87496E+00   0.48595E+00   0.10009E+01
0.87496E+00   -0.48595E+00   0.10009E+01
0.93896E+00   0.34135E+00   0.99909E+00
0.93896E+00   -0.34135E+00   0.99909E+00

POLE LOCATIONS (REAL,IMAG) AND RADIUS
0.90781E+00   0.40813E+00   0.99533E+00
0.90781E+00   -0.40813E+00   0.99533E+00
0.90475E+00   0.40493E+00   0.99123E+00
0.90475E+00   -0.40493E+00   0.99123E+00

SECTION 4 OUTPUT

REASSEMBLE COEFFICIENTS FROM POLES AND ZEROS

SINGLE FOURTH ORDER TRANSFER FUNCTION COEFFICIENTS

FOURTH ORDER NUMERATOR COEFFICIENTS (NORMALIZED)
```
 0.10000E+01    0.0
-0.36279E+01    0.0
 0.52861E+01    0.0
-0.36279E+01    0.0
 0.99988E+00    0.0
```

FOURTH ORDER DENOMINATOR COEFFICIENTS (NORMALIZED)
```
 0.10000E+01    0.0
-0.36251E+01    0.0
 0.52586E+01    0.0
-0.35766E+01   -0.18041E-15
 0.97339E+00    0.0
```


CASCADED SECOND ORDER TRANSFER FUNCTION COEFFICIENTS

FIRST STAGE QUADRATIC FUNCTION COEFFICIENTS

COMPLEX (REAL,IMAG) NUMERATOR COEFFICIENTS
```
 0.10000E+01    0.0       Z**2 +
-0.17499E+01    0.0       Z +
 0.10017E+01    0.0
```

COMPLEX (REAL,IMAG) DENOMINATOR COEFFICIENTS
```
 0.10000E+01    0.0       Z**2 +
-0.18156E+01    0.0       Z +
 0.99068E+00    0.0
```


SECOND STAGE QUADRATIC FUNCTION COEFFICIENTS

COMPLEX (REAL,IMAG) NUMERATOR COEFFICIENTS
```
 0.10000E+01    0.0       Z**2 +
-0.18779E+01    0.0       Z +
 0.99817E+00    0.0
```

COMPLEX (REAL,IMAG) DENOMINATOR COEFFICIENTS
```
 0.10000E+01    0.0       Z**2 +
-0.18095E+01    0.0       Z +
 0.98255E+00    0.0
```

```
C*****************************************************************************ABP00010
C                                                                          *ABP00020
C                            APPENDIX D                                     *ABP00030
C                                                                          *ABP00040
C                       FORTRAN PROGRAM ABPFR                               *ABP00050
C                                                                          *ABP00060
C                                                                          *ABP00070
C    .PROGRAM TO PLOT ANALOG BAND-PASS FILTER FREQUENCY AND PHASE           *ABP00080
C     RESPONSE OF THE ELLIPTIC FILTER TRANSFER FUNCTION                     *ABP00090
C                                                                          *ABP00100
C*****************************************************************************ABP00110
C    TYPE DECLARATIONS                                                      ABP00120
      IMPLICIT REAL(A-H,O-Z),INTEGER(I-N)                                   ABP00130
      REAL W(1001),HMAG(1001),HMAGN(1001),HMAGDB(1001),WX,F(1001)           ABP00140
      REAL A(5),B(5),HPHASE(1001)  .                                        ABP00150
      COMPLEX S,H                                                           ABP00160
C    NORMALIZED ANALOG TRANSFER FUNCTION COEFFICIENTS                       ABP00170
  .   A(1) = 1.                                                             ABP00180
      A(2) = 0.0                                                            ABP00190
      A(3) = 0.30513E+8                                                     ABP00200
      A(4) = 0.0                                                            ABP00210
      A(5) = 0.20198E+15                                                    ABP00220
      B(1) = 1.0                                                            ABP00230
      B(2) = 0.24729E+3                                                     ABP00240
      B(3) = 0.28507E+8                                                     ABP00250
      B(4) = 0.35145E+10                                                    ABP00260
      B(5) = 0.20198E+15                                                    ABP00270
C    CONSTANTS                                                              ABP00280
      PI = 3.1415927                                                        ABP00290
C    EVALUATE MAGNITUDE AND PHASE OF H(JW)                                  ABP00300
      DO 10 I = 1,1001                                                      ABP00310
         F(I) = FLOAT(I-1)                                                  ABP00320
         W(I) = (2.*PI*F(I))                                                ABP00330
         S = CMPLX(0.,W(I))                                                 ABP00340
         H = (A(1)*(S**4)+A(2)*(S**3)+A(3)*(S**2)+A(4)*S+A(5))/             ABP00350
     &(B(1)*(S**4)+B(2)*(S**3)+B(3)*(S**2)+B(4)*S+B(5))                     ABP00360
         HMAG(I) = CABS(H)                                                  ABP00370
         X = REAL(H)                                                        ABP00380
         Y = AIMAG(H)                                                       ABP00390
         HPHASE(I) = ATAN(Y/X)*180./PI                                      ABP00400
   10 CONTINUE                                                              ABP00410
C    NORMALIZE MAGNITUDE                                                    ABP00420
      AMAX = 0.0                                                            ABP00430
      DO 20 I = 1,1001                                                      ABP00440
         IF(HMAG(I).GT.AMAX) AMAX = HMAG(I)                                 ABP00450
   20 CONTINUE                                                              ABP00460
      DO 30 I = 1,1001                                                      ABP00470
         HMAGN(I) = HMAG(I)/AMAX                                           ABP00480
         HMAGDB(I) = 20.0 * ALOG10(HMAG(I))                                ABP00490
   30 CONTINUE                                                              ABP00500
      DO 40 I = 1,1001                                                      ABP00510
         WRITE (4,50)I,F(I),W(I),HMAG(I),HMAGN(I),HMAGDB(I),HPHASE(I)       ABP00520
   50 FORMAT(I4,6(1X,E10.3))                                                ABP00530
   40 CONTINUE                                                              ABP00540
C-------------------------------------------------------------------- ABP00550
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C GRAPHICS PARAMETERS FOR MAGNITUDE VS FREQUENCY                       ABP00560
C-------------------------------------------------------------------- ABP00570
      CALL LRGBUF                                                      ABP00580
      CALL COMPRS                                                      ABP00590
C     CALL TEK618                                                      ABP00600
C     CALL VRSTEC(0,0,0)                                               ABP00610
C .....    SETUP THE PLOTTING AREA                                     ABP00620
      CALL PAGE (11.0,8.5)                                             ABP00630
      CALL NOBRDR                                                      ABP00640
      CALL AREA2D(9.0,6.5)                                             ABP00650
C .....   LABEL THE X & Y AXES                                         ABP00660
      CALL XNAME('FREQUENCY (HZ)$',100)                                ABP00670
      CALL YNAME('AMPLITUDE$',100)                                     ABP00680
      CALL HEADIN('ANALOG ELLIPTIC BPF FREQUENCY RESPONSE$',100,1.6,2) ABP00690
      CALL HEADIN('AMPLITUDE VS FREQ (F0=600 HZ)$',100,1.,2)           ABP00700
C .....   DEFINE THE AXES                                              ABP00710
      CALL GRAF(0.0,'SCALE',1000.,-0.5,'SCALE',+1.5)                   ABP00720
C..... DRAW THE CURVES                                                 ABP00730
C     CALL THKCRV(0.02)                                                ABP00740
      CALL MARKER(15)                                                  ABP00750
      CALL CURVE(F,HMAGN,1001,0)                                       ABP00760
C..... TERMINATE THIS PLOT                                             ABP00770
      CALL ENDPL(0)                                                    ABP00780
C-------------------------------------------------------------------- ABP00790
C GRAPHICS PARAMETERS FOR MAGNITUDE IN DBS VS FREQUENCY                ABP00800
C-------------------------------------------------------------------- ABP00810
      CALL LRGBUF                                                      ABP00820
      CALL COMPRS                                                      ABP00830
C     CALL TEK618                                                      ABP00840
C     CALL VRSTEC(0,0,0)                                               ABP00850
C .....    SETUP THE PLOTTING AREA                                     ABP00860
      CALL PAGE (11.0,8.5)                                             ABP00870
      CALL NOBRDR                                                      ABP00880
      CALL AREA2D(9.0,6.5)                                             ABP00890
C .....   LABEL THE X & Y AXES                                         ABP00900
      CALL XNAME('FREQUENCY (HZ)$',100)                                ABP00910
      CALL YNAME('AMPLITUDE (DB)$',100)                                ABP00920
      CALL HEADIN('ANALOG ELLIPTIC BPF FREQUENCY RESPONSE$',100,1.6,2) ABP00930
      CALL HEADIN('AMPLITUDE (DB) VS FREQ (F0=600 HZ)$',100,1.,2)      ABP00940
C .....   DEFINE THE AXES                                              ABP00950
      CALL GRAF(0.0,'SCALE',1000.,-60.0,'SCALE',30.0)                  ABP00960
C..... DRAW THE CURVES                                                 ABP00970
C     CALL THKCRV(0.02)                                                ABP00980
      CALL MARKER(15)                                                  ABP00990
      CALL CURVE(F,HMAGDB,1001,0)                                      ABP01000
C..... TERMINATE THIS PLOT                                             ABP01010
      CALL ENDPL(0)                                                    ABP01020
C-------------------------------------------------------------------- ABP01030
C GRAPHICS PARAMETERS FOR PHASE VS FREQUENCY                           ABP01040
C-------------------------------------------------------------------- ABP01050
      CALL LRGBUF                                                      ABP01060
      CALL COMPRS                                                      ABP01070
C     CALL TEK618                                                      ABP01080
C     CALL VRSTEC(0,0,0)                                               ABP01090
C .....    SETUP THE PLOTTING AREA                                     ABP01100
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      CALL PAGE (11.0,8.5)                                     ABP01110
      CALL NOBRDR                                              ABP01120
      CALL AREA2D(9.0,6.5)                                     ABP01130
C .....   LABEL THE X & Y AXES                                ABP01140
      CALL XNAME('FREQUENCY (HZ)$',100)                        ABP01150
      CALL YNAME('PHASE (DEGREES)$',100)                       ABP01160
      CALL HEADIN('ANALOG ELLIPTIC BPF PHASE RESPONSE$',100,1.6,2)  ABP01170
      CALL HEADIN ('PHASE VS FREQ (FO=600 HZ)$',100,1.,2)      ABP01180
C .....   DEFINE THE AXES                                     ABP01190
      CALL GRAF(0.0,'SCALE',1000.,-100.,'SCALE',100.)          ABP01200
C..... DRAW THE CURVES                                        ABP01210
C     CALL THKCRV(0.02)                                       ABP01220
      CALL MARKER(15)                                          ABP01230
      CALL CURVE(F,HPHASE,1001,0)                              ABP01240
C..... TERMINATE THIS PLOT                                    ABP01250
      CALL ENDPL(0)                                            ABP01260
      CALL DONEPL                                              ABP01270
      STOP                                                     ABP01280
      END                                                      ABP01290
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       DN223(1)=0.998169                                              S2200560
       DD223(3)=1.                                                    S2200570
       DD223(2)=-1.809446                                             S2200580
       DD223(1)=0.982544                                              S2200590
C PRINT SECOND STAGE TRANSFER FUNCTION                                S2200600
       WRITE(4,82)DN223(3),DN223(2),DN223(1),DD223(3),DD223(2),DD223(1) S2200610
   82 FORMAT(' SECOND STAGE TRANSFER FUNCTION (2920 EQUIVALENT)',//,  S2200620
      &' ',E14.6,' + ',E14.6,' Z**-1 + ',E14.6,' Z**-2',/,            S2200630
      &'  -----------------------------------------------------------',/,S2200640
      &' ',E14.6,' + ',E14.6,' Z**-1 + ',E14.6,' Z**-2',///)          S2200650
C INITIALIZE VARIABLES                                                S2200660
       PI=3.1415927                                                   S2200670
       SCALS1=0.                                                      S2200680
       SCALS2=0.                                                      S2200690
C SAMPLE PERIOD = T = 1.1521152 X 10**-4 SECONDS                      S2200700
       T=4.*192./6.666E6                                              S2200710
C COMPUTE SCALE SUM FOR STAGES TO LIMIT INPUT AMPLITUDE               S2200720
       DO 6 K=1,3                                                     S2200730
          SCALS1=SCALS1+ABS(DN213(K))                                 S2200740
          SCALS1=SCALS1+ABS(DD213(K))                                 S2200750
          SCALS2=SCALS2+ABS(DN223(K))                                 S2200760
          SCALS2=SCALS2+ABS(DD223(K))                                 S2200770
    6 CONTINUE                                                        S2200780
C ENSURE SCALE SUM FACTORS WILL LIMIT OUTPUT TO LESS THAN ONE         S2200790
       SCALS1=SCALS1+1.E-6                                            S2200800
       SCALS2=SCALS2+1.E-6                                            S2200810
C COMPUTE SIMULATED INPUT MAGNITUDE LIMIT                             S2200820
       SINMAG=1./(SCALS1*SCALS2)                                      S2200830
C PRINT STAGE SCALE SUMS AND INPUT MAGNITUDE LIMIT                    S2200840
       WRITE(4,85)SCALS1,SCALS2,SINMAG                                S2200850
   85 FORMAT(//,' SCALE FACTORS AND INPUT MAGNITUDE LIMIT',//,        S2200860
      &' FIRST STAGE SCALE SUM = ',E14.6,/,                           S2200870
      &' SECOND STAGE SCALE SUM = ',E14.6,/,                          S2200880
      &' INPUT AMPLITUDE LIMITED TO +/- ',E14.6,///)                  S2200890
       WRITE(4,86)                                                    S2200900
   86 FORMAT('1')                                                     S2200910
C BEGIN SIMULATION FOR SPECIFIED FREQUENCIES GIVEN BY F(L)            S2200920
C*******************************                                      S2200930
C ADJUST AS NECESSARY                                                 S2200940
       DO 20 L=1,6                                                    S2200950
C*******************************                                      S2200960
C COMPUTE SIMULATION RUN INPUT CONSTANT FOR EACH FREQUENCY            S2200970
       TWOPIF=2.*PI*F(L)                                              S2200980
C INITIALIZE STAGE INPUTS AND OUTPUTS                                 S2200990
       IMOUT=0                                                        S2201000
       MOUT=0.                                                        S2201010
       DO 5 I=1,3                                                     S2201020
          X1(I)=0.                                                    S2201030
          X2(I)=0.                                                    S2201040
          Y1(I)=0.                                                    S2201050
          Y2(I)=0.                                                    S2201060
    5     CONTINUE                                                    S2201070
C PRINT SIMULATION HEADINGS                                           S2201080
       WRITE(4,98)F(L)                                                S2201090
   98     FORMAT(' FILTER FREQUENCY RESPONSE FOR F = ',F5.0,' HZ',/)  S2201100
```

```
C***************************************************************************S2200010
C                                                                          *S2200020
C                              APPENDIX G                                   *S2200030
C                                                                          *S2200040
C                         FORTRAN PROGRAM S22F                              *S2200050
C                                                                          *S2200060
C                                                                          *S2200070
C        THIS PROGRAM SIMULATES THE EXECUTION OF A 2920 PROGRAM            *S2200080
C        FOR A 600 HZ BANDPASS FILTER TRANSFER FUNCTION WHICH IS THE       *S2200090
C        PRODUCT OF TWO SECOND ORDER FILTER SECTIONS                       *S2200100
C                                                                          *S2200110
C                  Y(Z)    DN213(Z)    DN223(Z)                            *S2200120
C         H(Z) = ---- = -------- X --------                                *S2200130
C                  X(Z)    DD213(Z)    DD223(Z)                            *S2200140
C                                                                          *S2200150
C        THE SIMULATION IS PERFORMED OVER A RANGE OF DIFFERENT INPUT       *S2200160
C        FREQUENCIES ABOUT THE TARGET CENTER FREQUENCY OF 600 HZ           *S2200170
C                                                                          *S2200180
C***************************************************************************S2200190
C VARIABLE DECLARATIONS                                                     S2200200
      INTEGER IMOUT                                                         S2200210
      REAL TX,INO,OUTO,F(9)                                                 S2200220
      REAL X1(3),X2(3),Y1(3),Y2(3)                                         S2200230
      REAL SCALS1,SCALS2,SINMAG,MOUT                                        S2200240
      REAL DN213(3),DD213(3),DN223(3),DD223(3),T,PI,TWOPIF                 S2200250
C INPUT FREQUENCIES                                                         S2200260
      F(1)=500.                                                             S2200270
      F(2)=575.                                                             S2200280
      F(3)=590.825                                                          S2200290
      F(4)=600.                                                             S2200300
      F(5)=625.                                                             S2200310
      F(6)=700.                                                             S2200320
C     F(7)=                                                                 S2200330
C     F(8)=                                                                 S2200340
C     F(9)=                                                                 S2200350
      WRITE(4,80)                                                           S2200360
   80 FORMAT(' PROGRAM S22F OUTPUT',//,                                     S2200370
     &' FOURTH ORDER FILTER FREQUENCY RESPONSE',/,                         S2200380
     &'   (CASCADED SECOND ORDER SECTIONS)',///)                           S2200390
C FIRST SECOND ORDER STAGE COEFFICIENTS                                     S2200400
      DN213(3)=1.                                                           S2200410
      DN213(2)=-1.749875                                                    S2200420
      DN213(1)=1.001585                                                     S2200430
      DD213(3)=1.                                                           S2200440
      DD213(2)=-1.81555                                                     S2200450
      DD213(1)=0.990601                                                     S2200460
C PRINT FIRST STAGE TRANSFER FUNCTION                                       S2200470
      WRITE(4,81)DN213(3),DN213(2),DN213(1),DD213(3),DD213(2),DD213(1)     S2200480
   81 FORMAT(' FIRST STAGE TRANSFER FUNCTION (2920 EQUIVALENT)',//,        S2200490
     &' ',E14.6,' + ',E14.6,' Z**-1 + ',E14.6,' Z**-2',/,                  S2200500
     &' --------------------------------------------------------',//,S2200510
     &' ',E14.6,' + ',E14.6,' Z**-1 + ',E14.6,' Z**-2',///)              S2200520
C SECOND SECOND ORDER STAGE COEFFICIENTS                                    S2200530
      DN223(3)=1.                                                           S2200540
      DN223(2)=-1.877805                                                    S2200550
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      CALL ENDPL(0)                                          S2202210
      CALL DONEPL                                             S2202220
      STOP                                                    S2202230
      END                                                     S2202240
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       CALL CROSS                                                    S2201660
       CALL GRAF(0.,100.,1100.,0.0,0.5,2.5)                          S2201670
C..... DRAW THE BAR CURVES                                           S2201680
       CALL BARPAT(16)                                               S2201690
       CALL BARWID(0.02)                                             S2201700
       CALL VBARS(XKHZ,Z,YMAG,128)                                   S2201710
C..... TERMINATE THIS PLOT                                           S2201720
       CALL ENDPL(0)                                                 S2201730
C-------------------------------------------------------------------- S2201740
C GRAPHICS PARAMETERS FOR YPHASE VS K                                S2201750
C-------------------------------------------------------------------- S2201760
       CALL LRGBUF                                                   S2201770
C      CALL TEK618                                                   S2201780
       CALL COMPRS                                                   S2201790
C .....     SETUP THE PLOTTING AREA                                  S2201800
       CALL PAGE (11.0,8.5)                                          S2201810
       CALL NOBRDR                                                   S2201820
       CALL AREA2D(9.0,6.5)                                          S2201830
C ..... LABEL THE X & Y AXES                                         S2201840
       CALL XNAME('FREQUENCY (HZ) $',100)                            S2201850
       CALL YNAME('PHASE (RADS)$',100)                               S2201860
       CALL HEADIN ('DFT OF DIGITAL FILTER IMPULSE RESPONSE$',100,1.6,2) S2201870
       CALL HEADIN ('PHASE VS FREQUENCY$',100,1.,2)                  S2201880
C .....    DEFINE THE AXES                                           S2201890
       CALL CROSS                                                    S2201900
       CALL GRAF(0.,100.,1100.,-2.0,0.5,2.0)                         S2201910
C..... DRAW THE PHASE CURVE                                          S2201920
       CALL THKCRV(0.01)                                             S2201930
       CALL MARKER(15)                                               S2201940
       CALL CURVE(XKHZ,YPH,128,0)                                    S2201950
C..... TERMINATE THIS PLOT                                           S2201960
       CALL ENDPL(0)                                                 S2201970
C-------------------------------------------------------------------- S2201980
C GRAPHICS PARAMETERS FOR IMPULSE RESPONSE VS N                      S2201990
C-------------------------------------------------------------------- S2202000
       CALL LRGBUF                                                   S2202010
C      CALL TEK618                                                   S2202020
       CALL COMPRS                                                   S2202030
C .....     SETUP THE PLOTTING AREA                                  S2202040
       CALL PAGE (11.0,8.5)                                          S2202050
       CALL NOBRDR                                                   S2202060
       CALL AREA2D(9.0,6.5)                                          S2202070
C ..... LABEL THE X & Y AXES                                         S2202080
       CALL XNAME('ITERATION (N) $',100)                             S2202090
       CALL YNAME('MAGNITUDE$',100)                                  S2202100
       CALL HEADIN ('DIGITAL FILTER IMPULSE RESPONSE$',100,1.6,3)    S2202110
       CALL HEADIN ('OUTPUT VS ITERATION $',100,1.,3)                S2202120
       CALL HEADIN ('INPUT = .017 (SINMAG) AT T = 0$',100,1.,3)      S2202130
C .....    DEFINE THE AXES                                           S2202140
       CALL GRAF(0.,64.,1024.,-.03,.01,.03)                          S2202150
C..... DRAW THE IMPULSE RESPONSE CURVE                               S2202160
       CALL THKCRV(0.01)                                             S2202170
       CALL MARKER(15)                                               S2202180
       CALL CURVE(XK,XN,1024,0)                                      S2202190
C..... TERMINATE THIS PLOT                                           S2202200
```

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C PRINT PARAMETERS FOR EACH SIMULATION ITERATION              S2201110
C*************************************                         S2201120
            IM1=I-1                                            S2201130
            WRITE(4,100)IM1,TX,X1(1),Y2(1)                    S2201140
  100       FORMAT(1X,I4,2X,3(F13.6,2X))                      S2201150
C USE THIS OUTPUT FORMAT FOR EASYPLOT ROUTINE                 S2201160
C           WRITE(4,100)TX,X1(1),Y2(1)                        S2201170
C 100       FORMAT(1X,3(F15.8,2X))                            S2201180
C*************************************                         S2201190
C PERFORM SIMULATION SHIFT DELAY                              S2201200
            DO 15 J=2,3,1                                     S2201210
               Y1(5-J)=Y1(4-J)                               S2201220
               X1(5-J)=X1(4-J)                               S2201230
               Y2(5-J)=Y2(4-J)                               S2201240
               X2(5-J)=X2(4-J)                               S2201250
  15        CONTINUE                                          S2201260
  10     CONTINUE                                             S2201270
 -20 CONTINUE                                                 S2201280
C    THIS PROGRAM CALCULATES THE DFT OF THE IMPULSE RESPONSE  S2201290
C    OVER 1024 VALUES.  THIS IMPLIES M = 9 (2**9=1024).  IWK IS AN S2201300
C    INTEGER VECTOR FOR FFT2C CALCULATION OF LENGTH M+1 = 10  S2201310
     M=10                                                     S2201320
     DO 30 I=1,1024                                           S2201330
        A(I)=CONJG(A(I))                                      S2201340
  30 CONTINUE                                                 S2201350
     CALL FFT2C(A,M,IWK)                                      S2201360
     WRITE(4,38)                                              S2201370
  38 FORMAT(///,1X,'DFT IMPULSE RESPONSE OUTPUT OVER 1024 ITERATIONS' S2201380
    &,/,'      K            YMAG            YPHASE',/)         S2201390
     DO 40 I=1,1024                                           S2201400
        Z(I-1)=0.                                             S2201410
        A(I)=CONJG(A(I))                                      S2201420
        XK(I)=FLOAT(I-1)                                      S2201430
        XKHZ(I)=(1./T)*(XK(I)/1024.)                          S2201440
        YMAG(I)=CABS(A(I))                                    S2201450
        YPH(I)=ATAN(AIMAG(A(I))/REAL(A(I)))                   S2201460
        WRITE(4,39)XK(I),YMAG(I),YPH(I)                       S2201470
  39    FORMAT(1X,F8.0,4X,F12.4,4X,F12.4)                     S2201480
  40 CONTINUE                                                 S2201490
C-------------------------------------------------------------S2201500
C GRAPHICS PARAMETERS FOR YMAG VS K                           S2201510
C-------------------------------------------------------------S2201520
     CALL LRGBUF                                              S2201530
C    CALL TEK618                                              S2201540
     CALL COMPRS                                              S2201550
C .....     SETUP THE PLOTTING AREA                           S2201560
     CALL PAGE (11.0,8.5)                                     S2201570
     CALL NOBRDR                                              S2201580
     CALL AREA2D(9.0,6.5)                                     S2201590
C .....  LABEL THE X & Y AXES                                 S2201600
     CALL XNAME('FREQUENCY (HZ)$',100)                        S2201610
     CALL YNAME('MAGNITUDE$',100)                             S2201620
     CALL HEADIN ('DFT OF DIGITAL FILTER IMPULSE RESPONSE$',100,1.6,2) S2201630
     CALL HEADIN ('MAGNITUDE VS FREQUENCY$',100,1.,2)         S2201640
C .....   DEFINE THE AXES                                     S2201650
```

```
      SCALS1=0.                                                  S2200560
      SCALS2=0.                                                  S2200570
C SAMPLE PERIOD = T = 1.1521152 X 10**-4 SECONDS                S2200580
      T=4.*192./6.666E6                                          S2200590
C COMPUTE SCALE SUM FOR STAGES TO LIMIT INPUT AMPLITUDE         S2200600
      DO 6 K=1,3                                                 S2200610
         SCALS1=SCALS1+ABS(DN213(K))                            S2200620
         SCALS1=SCALS1+ABS(DD213(K))                            S2200630
         SCALS2=SCALS2+ABS(DN223(K))                            S2200640
         SCALS2=SCALS2+ABS(DD223(K))                            S2200650
    6 CONTINUE                                                   S2200660
C ENSURE SCALE SUM FACTORS WILL LIMIT OUTPUT TO LESS THAN ONE   S2200670
      SCALS1=SCALS1+1.E-6                                        S2200680
      SCALS2=SCALS2+1.E-6                                        S2200690
C COMPUTE SIMULATED INPUT MAGNITUDE LIMIT                       S2200700
      SINMAG=1./(SCALS1*SCALS2)                                  S2200710
C PRINT STAGE SCALE SUMS AND INPUT MAGNITUDE LIMIT              S2200720
      WRITE(4,85)SCALS1,SCALS2,SINMAG                           S2200730
   85 FORMAT(//,'SCALE FACTORS AND INPUT MAGNITUDE LIMIT',//,   S2200740
     &'FIRST STAGE SCALE SUM = ',E14.6,/,                       S2200750
     &'SECOND STAGE SCALE SUM = ',E14.6,/,                      S2200760
     &'INPUT AMPLITUDE LIMITED TO +/- ',E14.6,///)              S2200770
C PERFORM IMPULSE RESPONSE SIMULATION                           S2200780
C INITIALIZE STAGE INPUTS AND OUTPUTS                           S2200790
      DO 5 I=1,3                                                 S2200800
         X1(I)=0.                                                S2200810
         X2(I)=0.                                                S2200820
         Y1(I)=0.                                                S2200830
         Y2(I)=0.                                                S2200840
    5 CONTINUE                                                   S2200850
C PRINT SIMULATION HEADINGS                                     S2200860
      WRITE(4,98)                                                S2200870
   98    FORMAT(///,'FILTER IMPULSE RESPONSE',//)               S2200880
      WRITE(4,99)                                                S2200890
   99    FORMAT(/,'   I      TIME           IN1           OUT2',//) S2200900
C COMPUTE SIMULATED FILTER RESPONSE OVER INDICATED NUMBER OF SAMPLES (I)S2200910
C*******************************                                S2200920
C ADJUST AS NECESSARY                                           S2200930
      DO 10 I=1,1024                                            S2200940
C*******************************                                S2200950
C IN1 = X1(1) = IMPULSE INPUT AT T=0.                           S2200960
      IF (I.EQ.1) X1(1)=SINMAG                                   S2200970
      IF (I.NE.1) X1(1)=0.                                       S2200980
C TX = TOTAL ELAPSED SAMPLE TIME                                S2200990
      TX=T*FLOAT(I-1)                                            S2201000
C OUT1 = Y1(1) = FIRST STAGE OUTPUT = IN2 = X2(1) = SECOND STAGE INPUT S2201010
      Y1(1)=DN213(3)*X1(1)+DN213(2)*X1(2)+DN213(1)*X1(3)-       S2201020
     &     DD213(2)*Y1(2)-DD213(1)*Y1(3)                        S2201030
      X2(1)=Y1(1)                                               S2201040
C OUT2 = Y2(1) = SECOND STAGE OUTPUT = FILTER OUTPUT            S2201050
      Y2(1)=DN223(3)*X2(1)+DN223(2)*X2(2)+DN223(1)*X2(3)-       S2201060
     &     DD223(2)*Y2(2)-DD223(1)*Y2(3)                        S2201070
      XN(I)=Y2(1)                                               S2201080
C FORM COMPLEX ARRAY OF IMPULSE VALUES FOR DFT                  S2201090
      A(I)=CMPLX(Y2(1),0.)                                      S2201100
```

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C**********************************************************************S2200010
C                                                                    *S2200020
C       THIS PROGRAM SIMULATES THE EXECUTION OF A 2920 PROGRAM        *S2200030
C       FOR A 600 HZ BANDPASS FILTER TRANSFER FUNCTION WHICH IS THE   *S2200040
C       PRODUCT OF TWO SECOND ORDER FILTER SECTIONS                   *S2200050
C                                                                    *S2200060
C              Y(Z)    DN213(Z)    DN223(Z)                           *S2200070
C       H(Z) = ---- = -------- X --------                            *S2200080
C              X(Z)    DD213(Z)    DD223(Z)                           *S2200090
C                                                                    *S2200100
C       THE SIMULATION IS PERFORMED FOR AN IMPULSE INPUT EQUAL TO THE *S2200110
C       GREATEST ALLOWABLE INPUT (SINMAG) AT T=0.  WE THEN EXAMINE    *S2200120
C       THE FAST FOURIER TRANSFORM OF THE IMPULSE SEQUENCE OVER 1024  *S2200130
C       SAMPLES TO CONFIRM THE FREQUENCY RESPONSE OF THE SYSTEM.      *S2200140
C                                                                    *S2200150
C**********************************************************************S2200160
C VARIABLE DECLARATIONS                                               S2200170
  .    INTEGER IM1,M,IWK(11)                                          S2200180
       REAL X1(3),X2(3),Y1(3),Y2(3)                                   S2200190
       REAL SCALS1,SCALS2,SINMAG                                      S2200200
       REAL DN213(3),DD213(3),DN223(3),DD223(3),T,TX                  S2200210
       COMPLEX A(1024)                                                S2200220
       REAL XK(1024),XKHZ(1024),XN(1024),YMAG(1024),YPH(1024),Z(1024) S2200230
C PRINT OUTPUT HEADING                                                S2200240
       WRITE(4,80)                                                    S2200250
   80 FORMAT('EIGHTH ORDER FILTER IMPULSE RESPONSE',/,                S2200260
      &'   (CASCADED SECOND ORDER SECTIONS)',/,                       S2200270
      &'(SECOND FOURTH ORDER BLOCK OF EIGHTH ORDER FILTER)',//)       S2200280
C FIRST SECOND ORDER STAGE COEFFICIENTS                               S2200290
       DN213(3)=1.                                                    S2200300
       DN213(2)=-1.749875                                             S2200310
       DN213(1)=1.001585                                              S2200320
       DD213(3)=1.                                                    S2200330
       DD213(2)=-1.81555                                              S2200340
       DD213(1)=0.990601                                              S2200350
C PRINT FIRST STAGE TRANSFER FUNCTION                                 S2200360
       WRITE(4,81)DN213(3),DN213(2),DN213(1),DD213(3),DD213(2),DD213(1)S2200370
   81 FORMAT('SECOND FIRST STAGE TRANSFER FUNCTION',//,   .           S2200380
      &E14.6,' + ',E14.6,' Z**-1 + ',E14.6,' Z**-2',/,                S2200390
      &' ----------------------------------------------------',//,S2200400
      &E14.6,' + ',E14.6,' Z**-1 + ',E14.6,' Z**-2',///)             S2200410
C SECOND SECOND ORDER STAGE COEFFICIENTS                              S2200420
       DN223(3)=1.                                                    S2200430
       DN223(2)=-1.877805                                             S2200440
       DN223(1)=0.998169                                              S2200450
       DD223(3)=1.                                                    S2200460
       DD223(2)=-1.809446                                             S2200470
       DD223(1)=0.982544                                              S2200480
C PRINT SECOND STAGE TRANSFER FUNCTION                                S2200490
       WRITE(4,82)DN223(3),DN223(2),DN223(1),DD223(3),DD223(2),DD223(1)S2200500
   82 FORMAT('SECOND SECOND STAGE TRANSFER FUNCTION',//,              S2200510
      &E14.6,' + ',E14.6,' Z**-1 + ',E14.6,' Z**-2',/,                S2200520
      &' ----------------------------------------------------',//,S2200530
      &E14.6,' + ',E14.6,' Z**-1 + ',E14.6,' Z**-2',///)             S2200540
C INITIALIZE VARIABLES                                                S2200550
```

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S221 PROGRAM OUTPUT

FOURTH ORDER FILTER IMPULSE RESPONSE
  (CASCADED SECOND ORDER SECTIONS)

FIRST STAGE TRANSFER FUNCTION (2920 COEFFICIENTS)

    0.100000E+01 + -0.174988E+01 Z**-1 +   0.100159E+01 Z**-2

    0.100000E+01 + -0.181555E+01 Z**-1 +   0.990601E+00 Z**-2

SECOND STAGE TRANSFER FUNCTION (2920 COEFFICIENTS)

    0.100000E+01 + -0.187780E+01 Z**-1 +   0.998169E+00 Z**-2

    0.100000E+01 + -0.180945E+01 Z**-1 +   0.982554E+00 Z**-2

SCALE FACTORS AND INPUT MAGNITUDE LIMIT

FIRST STAGE SCALE SUM =   0.755761E+01
SECOND STAGE SCALE SUM =   0.766797E+01
INPUT AMPLITUDE LIMITED TO +/-   0.172558E-01

FILTER IMPULSE RESPONSE

MAX AMPLITUDE OF IMPULSE RESPONSE OVER   512 ITERATIONS = 0.011935
MAX AMPLITUDE OF IMPULSE RESPONSE OVER   1024 ITERATIONS = 0.011935
MAX AMPLITUDE OF IMPULSE RESPONSE OVER   1536 ITERATIONS = 0.011935
MAX AMPLITUDE OF IMPULSE RESPONSE OVER   2048 ITERATIONS = 0.011935
MAX AMPLITUDE OF IMPULSE RESPONSE OVER   2560 ITERATIONS = 0.011935
MAX AMPLITUDE OF IMPULSE RESPONSE OVER   3072 ITERATIONS = 0.011935
MAX AMPLITUDE OF IMPULSE RESPONSE OVER   3584 ITERATIONS = 0.011935
MAX AMPLITUDE OF IMPULSE RESPONSE OVER   4096 ITERATIONS = 0.011935
MAX AMPLITUDE OF IMPULSE RESPONSE OVER   4608 ITERATIONS = 0.011935
MAX AMPLITUDE OF IMPULSE RESPONSE OVER   5120 ITERATIONS = 0.011935
MAX AMPLITUDE OF IMPULSE RESPONSE OVER   5632 ITERATIONS = 0.011935
MAX AMPLITUDE OF IMPULSE RESPONSE OVER   6144 ITERATIONS = 0.011935
MAX AMPLITUDE OF IMPULSE RESPONSE OVER   6656 ITERATIONS = 0.011935
MAX AMPLITUDE OF IMPULSE RESPONSE OVER   7168 ITERATIONS = 0.011935
MAX AMPLITUDE OF IMPULSE RESPONSE OVER   7680 ITERATIONS = 0.011935
MAX AMPLITUDE OF IMPULSE RESPONSE OVER   8192 ITERATIONS = 0.011935

MAX AMPLITUDE OCCURRED AT ITERATION   150

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     &    D2(2,2)*Y2(2)-D2(2,1)*Y2(3)                                  S2201110
          IF ((MXAMP.LT.(ABS(Y2(1)))).AND.(I.NE.1)) GO TO 30          S2201120
             GO TO 40                                                  S2201130
  30         MXAMP=ABS(Y2(1))                                          S2201140
             IMXAMP=I                                                  S2201150
  40         CONTINUE                                                  S2201160
C PRINT PARAMETERS FOR EACH SIMULATION ITERATION                       S2201170
C*****************************************                             S2201180
C         WRITE(4,100)IM1,TX,X1(1),Y2(1)                               S2201190
C 100      FORMAT(1X,I4,2X,3(F13.6,2X))                                S2201200
C USE THIS OUTPUT FORMAT FOR EASYPLOT ROUTINE                          S2201210
C         WRITE(4,100)TX,X1(1),Y2(1)                                   S2201220
C 100      FORMAT(1X,3(F15.8,2X))                                      S2201230
C*****************************************                             S2201240
C PERFORM SIMULATION SHIFT DELAY   .                                   S2201250
          DO 15 J=2,3,1                                                S2201260
             Y1(5-J)=Y1(4-J)                                           S2201270
  .          X1(5-J)=X1(4-J)                                           S2201280
             Y2(5-J)=Y2(4-J)                                           S2201290
             X2(5-J)=X2(4-J)                                           S2201300
  15      CONTINUE                                                     S2201310
          IF (MOD(I,512))10,14,10                                      S2201320
  14      WRITE(4,16)I,MXAMP                                           S2201330
  16      FORMAT(' MAX AMPLITUDE OF IMPULSE RESPONSE OVER ',I5,        S2201340
     &' ITERATIONS = ',F9.6)                                          S2201350
  10 CONTINUE                                                          S2201360
     WRITE(4,18)IMXAMP                                                 S2201370
  18 FORMAT(/,' MAX AMPLITUDE OCCURRED AT ITERATION ',I5)             S2201380
     STOP                                                              S2201390
     END                                                               S2201400
```

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      82 FORMAT(' SECOND STAGE TRANSFER FUNCTION (2920 COEFFICIENTS)',//,  S2200560
        &' ',E14.6,' + ',E14.6,' Z**-1 + ',E14.6,' Z**-2',/,               S2200570
        &'   -------------------------------------------------------------',//,  S2200580
        &' ',E14.6,' + ',E14.6,' Z**-1 + ',E14.6,' Z**-2',///)             S2200590
C INITIALIZE VARIABLES                                                     S2200600
        SCALS1=0.                                                          S2200610
        SCALS2=0.                                                          S2200620
C SAMPLE PERIOD = T = 1.1521152 X 10**-4 SECONDS                          S2200630
        T=4.*192./6.666E6                                                  S2200640
C COMPUTE SCALE SUM FOR STAGES TO LIMIT INPUT AMPLITUDE                    S2200650
        DO 6 K=1,3                                                         S2200660
            SCALS1=SCALS1+ABS(N2(1,K))                                     S2200670
            SCALS1=SCALS1+ABS(D2(1,K))                                     S2200680
            SCALS2=SCALS2+ABS(N2(2,K))                                     S2200690
            SCALS2=SCALS2+ABS(D2(2,K))                                     S2200700
      6 CONTINUE                                                           S2200710
C ENSURE SCALE SUM FACTORS WILL LIMIT OUTPUT TO LESS THAN ONE              S2200720
  .     SCALS1=SCALS1+1.E-6                                                S2200730
        SCALS2=SCALS2+1.E-6                                                S2200740
C COMPUTE SIMULATED INPUT MAGNITUDE LIMIT                                  S2200750
        SINMAG=1./(SCALS1*SCALS2)                                          S2200760
C PRINT STAGE SCALE SUMS AND INPUT MAGNITUDE LIMIT                         S2200770
        WRITE(4,85)SCALS1,SCALS2,SINMAG                                    S2200780
      85 FORMAT(//,' SCALE FACTORS AND INPUT MAGNITUDE LIMIT',///,          S2200790
        &' FIRST STAGE SCALE SUM = ',E14.6,/,                              S2200800
        &' SECOND STAGE SCALE SUM = ',E14.6,/,                             S2200810
        &' INPUT AMPLITUDE LIMITED TO +/- ',E14.6,////)                    S2200820
C PERFORM IMPULSE RESPONSE SIMULATION                                      S2200830
C INITIALIZE STAGE INPUTS AND OUTPUTS                                      S2200840
        DO 5 I=1,3                                                         S2200850
            X1(I)=0.                                                       S2200860
            X2(I)=0.                                                       S2200870
            Y1(I)=0.                                                       S2200880
            Y2(I)=0.                                                       S2200890
      5 CONTINUE                                                           S2200900
        MXAMP=0.                                                           S2200910
        IMXAMP=0                                                           S2200920
C PRINT SIMULATION HEADINGS                                                S2200930
        WRITE(4,98)                                                        S2200940
      98 FORMAT(' FILTER IMPULSE RESPONSE',//)                              S2200950
C       WRITE(4,99)                                                        S2200960
C  99 FORMAT(/,'   I      TIME           IN1          OUT2',//)            S2200970
C COMPUTE SIMULATED FILTER RESPONSE OVER REQUIRED ITERATIONS (NUMIT)       S2200980
        DO 10 I=1,NUMIT                                                    S2200990
C IN1 = X1(1) = IMPULSE INPUT AT T=0.                                      S2201000
        IF (I.EQ.1) X1(1)=SINMAG                                           S2201010
        IF (I.NE.1) X1(1)=0.                                               S2201020
C TX = TOTAL ELAPSED SAMPLE TIME                                           S2201030
        TX=T*FLOAT(I-1)                                                    S2201040
C OUT1 = Y1(1) = FIRST STAGE OUTPUT = IN2 = X2(1) = SECOND STAGE INPUT     S2201050
        Y1(1)=N2(1,3)*X1(1)+N2(1,2)*X1(2)+N2(1,1)*X1(3)-                   S2201060
      &    D2(1,2)*Y1(2)-D2(1,1)*Y1(3)                                     S2201070
        X2(1)=Y1(1)                                                        S2201080
C OUT2 = Y2(1) = SECOND STAGE OUTPUT = XN(I)                               S2201090
        Y2(1)=N2(2,3)*X2(1)+N2(2,2)*X2(2)+N2(2,1)*X2(3)-                   S2201100
```

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C*********************************************************************S2200010
C                                                                    *S2200020
C                              APPENDIX F                            *S2200030
C                                                                    *S2200040
C                         FORTRAN PROGRAM S221                       *S2200050
C                                                                    *S2200060
C                                                                    *S2200070
C        THIS PROGRAM SIMULATES THE EXECUTION OF A 2920 PROGRAM      *S2200080
C        FOR A FOURTH ORDER ELLIPTIC 600 HZ BANDPASS FILTER TRANSFER *S2200090
C        TRANSFER FUNCTION WHICH IS THE PRODUCT OF TWO SECOND ORDER  *S2200100
C        FILTER SECTIONS                                             *S2200110
C                                                                    *S2200120
C                     Y(Z)    N2(1,Z)     N2(2,Z)                    *S2200130
C           H(Z) =   ---- = ------- X  -------                       *S2200140
C                     X(Z)    D2(1,Z)     D2(2,Z)                    *S2200150
C                                                                    *S2200160
C        THE SIMULATION IS PERFORMED FOR AN IMPULSE INPUT EQUAL TO THE*S2200170
C  .     GREATEST ALLOWABLE INPUT (SINMAG) AT T=0 AND ALLOWED TO RUN *S2200180
C        OVER NUMIT ITERATIONS TO CHECK FOR STABILITY.               *S2200190
C                                                                    *S2200200
C*********************************************************************S2200210
C VARIABLE DECLARATIONS                                               S2200220
      INTEGER NUMIT,IMXAMP                                            S2200230
      REAL X1(3),X2(3),Y1(3),Y2(3)                                    S2200240
      REAL SCALS1,SCALS2,SINMAG,MXAMP                                 S2200250
      REAL N2(2,3),D2(2,3),T,TX                                       S2200260
C DECLARE NUMBER OF SIMULATION ITERATIONS                             S2200270
      NUMIT=8192                                                      S2200280
C PRINT OUTPUT HEADING                                                S2200290
      WRITE(4,80)                                                     S2200300
   80 FORMAT(' S221 PROGRAM OUTPUT',//,                               S2200310
     &' FOURTH ORDER FILTER IMPULSE RESPONSE',/,                      S2200320
     &'    (CASCADED SECOND ORDER SECTIONS)',///)                     S2200330
C FIRST SECOND ORDER STAGE COEFFICIENTS                               S2200340
      N2(1,3)=1.                                                      S2200350
      N2(1,2)=-1.749875                                               S2200360
      N2(1,1)=1.001585                                                S2200370
      D2(1,3)=1.                                                      S2200380
      D2(1,2)=-1.81555                                                S2200390
      D2(1,1)=0.990601                                                S2200400
C PRINT FIRST STAGE TRANSFER FUNCTION                                 S2200410
      WRITE(4,81)N2(1,3),N2(1,2),N2(1,1),D2(1,3),D2(1,2),D2(1,1)      S2200420
   81 FORMAT(' FIRST STAGE TRANSFER FUNCTION (2920 COEFFICIENTS)',//, S2200430
     &' ',E14.6,' + ',E14.6,' Z**-1 + ',E14.6,' Z**-2',/,            S2200440
     &' ------------------------------------------------------------',//,S2200450
     &' ',E14.6,' + ',E14.6,' Z**-1 + ',E14.6,' Z**-2',///)          S2200460
C SECOND SECOND ORDER STAGE COEFFICIENTS                              S2200470
      N2(2,3)=1.                                                      S2200480
      N2(2,2)=-1.877805                                               S2200490
      N2(2,1)=0.998169                                                S2200500
      D2(2,3)=1.                                                      S2200510
      D2(2,2)=-1.809446                                               S2200520
      D2(2,1)=0.982554                                                S2200530
C PRINT SECOND STAGE TRANSFER FUNCTION                                S2200540
      WRITE(4,82)N2(2,3),N2(2,2),N2(2,1),D2(2,3),D2(2,2),D2(2,1)      S2200550
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        CALL PAGE (11.0,8.5)                                          DBP01110
        CALL NOBRDR                                                   DBP01120
        CALL AREA2D(9.0,6.5)                                          DBP01130
C .....    LABEL THE X & Y AXES                                       DBP01140
        CALL XNAME('FREQUENCY (HZ)$',100)                             DBP01150
        CALL YNAME('PHASE (DEGREES)$',100)                            DBP01160
        CALL HEADIN('DIGITAL ELLIPTIC BPF PHASE RESPONSE$',100,1.6,2) DBP01170
        CALL HEADIN('PHASE (DEGREES) VS FREQ (F0=590 HZ)$',100,1.,2)  DBP01180
C .....    DEFINE THE AXES                                            DBP01190
        CALL GRAF(0.0,'SCALE',1200.,-100.,'SCALE',100.)               DBP01200
C..... DRAW THE CURVES                                                DBP01210
        CALL THKCRV(0.02)                                             DBP01220
        CALL MARKER(15)                                               DBP01230
        CALL CURVE(FREQ,HPHASE,201,0)                                 DBP01240
C..... TERMINATE THIS PLOT                                            DBP01250
        CALL ENDPL(0)                                                 DBP01260
        CALL DONEPL                                                   DBP01270
      . STOP                                                          DBP01280
        END                                                           DBP01290
```

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C GRAPHICS PARAMETERS FOR MAGNITUDE VS FREQUENCY (IN HZ)                    DBP00560
C-------------------------------------------------------------------------- DBP00570
      CALL LRGBUF                                                           DBP00580
C     CALL COMPRS                                                           DBP00590
      CALL TEK618                                                           DBP00600
C     CALL VRSTEC(0,0,0)                                                    DBP00610
C .....    SETUP THE PLOTTING AREA                                          DBP00620
      CALL PAGE (11.0,8.5)                                                  DBP00630
      CALL NOBRDR                                                           DBP00640
      CALL AREA2D(9.0,6.5)                                                  DBP00650
C .....  LABEL THE X & Y AXES                                               DBP00660
      CALL XNAME('FREQUENCY (HZ)$',100)                                     DBP00670
      CALL YNAME('AMPLITUDE$',100)                                          DBP00680
      CALL HEADIN('DIGITAL ELLIPTIC BPF FREQUENCY RESPONSE$',100,1.6,2)     DBP00690
      CALL HEADIN('NORMALIZED AMPLITUDE VS FREQ (FO=590 HZ)$',100,1.,2)     DBP00700
C .....    DEFINE THE AXES                                                  DBP00710
      CALL GRAF(0.0,'SCALE',1200.,-0.5,'SCALE',1.5)                         DBP00720
C..... DRAW THE CURVES                                                      DBP00730
      CALL THKCRV(0.02)                                                     DBP00740
      CALL MARKER(15)                                                       DBP00750
      CALL CURVE(FREQ,HMAGN,201,0)                                          DBP00760
C..... TERMINATE THIS PLOT                                                  DBP00770
      CALL ENDPL(0)                                                         DBP00780
C-------------------------------------------------------------------------- DBP00790
C GRAPHICS PARAMETERS FOR MAGNITUDE (IN DB) VS FREQUENCY (IN HZ)            DBP00800
C-------------------------------------------------------------------------- DBP00810
      CALL LRGBUF                                                           DBP00820
C     CALL COMPRS                                                           DBP00830
      CALL TEK618                                                           DBP00840
C     CALL VRSTEC(0,0,0)                                                    DBP00850
C .....    SETUP THE PLOTTING AREA                                          DBP00860
      CALL PAGE (11.0,8.5)                                                  DBP00870
      CALL NOBRDR                                                           DBP00880
      CALL AREA2D(9.0,6.5)                                                  DBP00890
C .....  LABEL THE X & Y AXES                                               DBP00900
      CALL XNAME('FREQUENCY (HZ)$',100)                                     DBP00910
      CALL YNAME('AMPLITUDE (DB)$',100)                                     DBP00920
      CALL HEADIN('DIGITAL ELLIPTIC BPF FREQUENCY RESPONSE$',100,1.6,2)     DBP00930
      CALL HEADIN('AMPLITUDE (DB) VS FREQ (FO=590 HZ)$',100,1.,2)           DBP00940
C .....    DEFINE THE AXES                                                  DBP00950
      CALL GRAF(0.0,'SCALE',1200.,20.0,'SCALE',1L .0)                       DBP00960
C..... DRAW THE CURVES                                                      DBP00970
      CALL THKCRV(0.02)                                                     DBP00980
      CALL MARKER(15)                                                       DBP00990
      CALL CURVE(FREQ,HMAGDB,201,0)                                         DBP01000
C..... TERMINATE THIS PLOT                                                  DBP01010
      CALL ENDPL(0)                                                         DBP01020
C-------------------------------------------------------------------------- DBP01030
C GRAPHICS PARAMETERS FOR PHASE VS FREQUENCY                                DBP01040
C-------------------------------------------------------------------------- DBP01050
      CALL LRGBUF                                                           DBP01060
      CALL COMPRS                                                           DBP01070
C     CALL TEK618                                                           DBP01080
C     CALL VRSTEC(0,0,0)                                                    DBP01090
C .....    SETUP THE PLOTTING AREA                                          DBP01100
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C*********************************************************************DBP00010
C                                                                   *DBP00020
C                              APPENDIX E                           *DBP00030
C                                                                   *DBP00040
C                       FORTRAN PROGRAM DBPFR                       *DBP00050
C                                                                   *DBP00060
C                                                                   *DBP00070
C     PROGRAM TO PLOT DIGITAL BAND-PASS FILTER FREQUENCY AND PHASE  *DBP00080
C     RESPONSE OF THE ELLIPTIC FILTER TRANSFER FUNCTION             *DBP00090
C                                                                   *DBP00100
C*********************************************************************DBP00110
C     TYPE DECLARATIONS                                              DBP00120
      IMPLICIT REAL(A-H,O-Z),INTEGER(I-N)                            DBP00130
      REAL OMEGA(201),HMAG(201),HPHASE(201),HMAGN(201),HMAGDB(201)   DBP00140
      REAL F(201),FREQ(201),FS,FSDIV2,TS                            DBP00150
      COMPLEX Z,H                                                    DBP00160
C     NORMALIZED TRANSFER FUNCTION COEFFICIENTS                      DBP00170
      A0 = 1.                                                        DBP00180
      A1 =-3.6279                                                    DBP00190
      A2 = 5.2861                                                    DBP00200
      A3 = A2                                                        DBP00210
      A4 = A1                                                        DBP00220
      B0 = 1.                                                        DBP00230
      B1 =-3.6251                                                    DBP00240
      B2 = 5.2586                                                    DBP00250
      B3 =-3.5768                                                    DBP00260
      B4 = 0.97353                                                   DBP00270
C     CONSTANTS                                                      DBP00280
      PI = 3.1415927                                                 DBP00290
      FS = 6.666E6/(4.*192.)                                         DBP00300
      TS=1./FS                                                       DBP00310
      FSDIV2 = FS/2.                                                 DBP00320
C     EVALUATE MAGNITUDE AND PHASE OF H(EXP(J*OMEGA*T))              DBP00330
      DO 10 I = 1,201                                                DBP00340
         F(I) = FLOAT(I-1)                                           DBP00350
         FREQ(I) = 6.*F(I)                                           DBP00360
         OMEGA(I) = (2.*PI.*FREQ(I)*TS)                              DBP00370
         Z = CMPLX(COS(OMEGA(I)),SIN(OMEGA(I)))                      DBP00380
         H = (A0+A1*Z**(-1)+A2*Z**(-2)+A3*Z**(-3)+A4*Z**(-4))/(B0+   DBP00390
     &B1*Z**(-1)+B2*Z**(-2)+B3*Z**(-3)+B4*Z**(-4))                   DBP00400
         HMAG(I) = CABS(H)                                           DBP00410
         X = REAL(H)                                                 DBP00420
         Y = AIMAG(H)                                                DBP00430
         HPHASE(I) = ATAN(Y/X)*180./PI                               DBP00440
   10 CONTINUE                                                       DBP00450
C     NORMALIZE MAGNITUDE                                            DBP00460
      AMAX = 0.0                                                     DBP00470
      DO 20 I = 1,201                                                DBP00480
         IF(HMAG(I).GT.AMAX) AMAX = HMAG(I)                          DBP00490
   20 CONTINUE                                                       DBP00500
      DO 30 I = 1,201                                                DBP00510
         HMAGN(I) = HMAG(I)/AMAX                                     DBP00520
         HMAGDB(I) = 20.0 * ALOG10(HMAG(I))                          DBP00530
   30 CONTINUE                                                       DBP00540
C------------------------------------------------------------------- DBP00550
```

```
C          WRITE(4,99)                                              S2201110
C  99      FORMAT(/,'   I     TIME      IN1      OUT1=IN2    OUT2',//) S2201120
C COMPUTE SIMULATED FILTER RESPONSE OVER INDICATED NUMBER OF SAMPLES (I)S2201130
C*******************************                                    S2201140
C ADJUST AS NECESSARY                                              S2201150
           DO 10 I=1,2048                                          S2201160
C*********************************                                  S2201170
C TX = TOTAL ELAPSED SAMPLE TIME                                   S2201180
           TX=T*FLOAT(I-1)                                         S2201190
C IN1 = X1(1) = FILTER FIRST STAGE INPUT VALUE (LIMITED BY SINMAG) S2201200
           X1(1)=SINMAG*SIN(TWOPIF*TX)                             S2201210
C OUT1 = Y1(1) = FIRST STAGE OUTPUT = IN2 = X2(1) = SECOND STAGE INPUT S2201220
           Y1(1)=DN213(3)*X1(1)+DN213(2)*X1(2)+DN213(1)*X1(3)-     S2201230
     &     DD213(2)*Y1(2)-DD213(1)*Y1(3)                           S2201240
           X2(1)=Y1(1)                                             S2201250
C OUT2 = Y2(1) = SECOND STAGE OUTPUT = FILTER OUTPUT               S2201260
           Y2(1)=DN223(3)*X2(1)+DN223(2)*X2(2)+DN223(1)*X2(3)-     S2201270
   .  &     DD223(2)*Y2(2)-DD223(1)*Y2(3)                          S2201280
C PRINT PARAMETERS FOR EACH SIMULATION ITERATION                   S2201290
C***************************************                            S2201300
C          WRITE(4,100)I,TX,X1(1),X2(1),Y2(1)                      S2201310
C 100      FORMAT(1X,I4,2X,4(F10.3,2X))                            S2201320
C USE THIS OUTPUT FORMAT FOR EASYPLOT ROUTINE                      S2201330
C          WRITE(4,100)TX,X1(1),Y2(1)                              S2201340
C 100      FORMAT(1X,3(F15.8,2X))                                  S2201350
C**************************************                             S2201360
C REMEMBER MAXIMUM AMPLITUDE IN EACH FREQUENCY SIMULATION TRIAL    S2201370
           IF (ABS(Y2(1))-MOUT) 11,11,14                           S2201380
   14          MOUT=ABS(Y2(1))                                     S2201390
               IMOUT=I                                             S2201400
C PERFORM SIMULATION SHIFT DELAY                                   S2201410
   11          DO 15 J=2,3,1                                       S2201420
               Y1(5-J)=Y1(4-J)                                     S2201430
               X1(5-J)=X1(4-J)                                     S2201440
               Y2(5-J)=Y2(4-J)                                     S2201450
               X2(5-J)=X2(4-J)                                     S2201460
   15      CONTINUE                                                S2201470
   10   CONTINUE                                                   S2201480
C PRINT MAXIMUM OUTPUT AMPLITUDE FOR EACH FREQUENCY SIMULATION RUN S2201490
        WRITE(4,89)MOUT,IMOUT                                      S2201500
   89      FORMAT('    MAXIMUM OUTPUT AMPLITUDE = ',F15.8,/,       S2201510
     &'    THIS OCCURRED AT SIMULATION ITERATION ',I5,///)          S2201520
   20 CONTINUE                                                     S2201530
      STOP                                                         S2201540
      END                                                          S2201550
```

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PROGRAM S22F OUTPUT

FOURTH ORDER FILTER FREQUENCY RESPONSE
 (CASCADED SECOND ORDER SECTIONS)

FIRST STAGE TRANSFER FUNCTION (2920 EQUIVALENT)

$$\frac{0.100000E+01 + -0.174988E+01 \ Z**-1 + 0.100159E+01 \ Z**-2}{0.100000E+01 + -0.181555E+01 \ Z**-1 + 0.990601E+00 \ Z**-2}$$

SECOND STAGE TRANSFER FUNCTION (2920 EQUIVALENT)

$$\frac{0.100000E+01 + -0.187780E+01 \ Z**-1 + 0.998169E+00 \ Z**-2}{0.100000E+01 + -0.180945E+01 \ Z**-1 + 0.982544E+00 \ Z**-2}$$

SCALE FACTORS AND INPUT MAGNITUDE LIMIT

FIRST STAGE SCALE SUM =   0.755761E+01
SECOND STAGE SCALE SUM =   0.766796E+01
INPUT AMPLITUDE LIMITED TO +/-   0.172558E-01

FILTER FREQUENCY RESPONSE FOR F = 500. HZ

  MAXIMUM OUTPUT AMPLITUDE =   0.10085225
  THIS OCCURRED AT SIMULATION ITERATION   180

FILTER FREQUENCY RESPONSE FOR F = 575. HZ

  MAXIMUM OUTPUT AMPLITUDE =   1.59343243
  THIS OCCURRED AT SIMULATION ITERATION   515

FILTER FREQUENCY RESPONSE FOR F = 591. HZ

  MAXIMUM OUTPUT AMPLITUDE =   1.62147427
  THIS OCCURRED AT SIMULATION ITERATION   500

FILTER FREQUENCY RESPONSE FOR F = 600. HZ

  MAXIMUM OUTPUT AMPLITUDE =   0.89969766
  THIS OCCURRED AT SIMULATION ITERATION   284

FILTER FREQUENCY RESPONSE FOR F = 625. HZ

  MAXIMUM OUTPUT AMPLITUDE =   0.30743510
  THIS OCCURRED AT SIMULATION ITERATION   135

FILTER FREQUENCY RESPONSE FOR F = 700. HZ

  MAXIMUM OUTPUT AMPLITUDE =   0.07697707
  THIS OCCURRED AT SIMULATION ITERATION   150

```
C******************************************************************S2200010
C                                                                 *S2200020
C        THIS PROGRAM SIMULATES THE EXECUTION OF A 2920 PROGRAM   *S2200030
C        FOR A 600 HZ BANDPASS FILTER TRANSFER FUNCTION WHICH IS THE *S2200040
C        PRODUCT OF TWO SECOND ORDER FILTER SECTIONS              *S2200050
C                                                                 *S2200060
C               Y(Z)    DN213(Z)    DN223(Z)                      *S2200070
C        H(Z) = ---- = -------- X --------                        *S2200080
C               X(Z)    DD213(Z)    DD223(Z)                      *S2200090
C                                                                 *S2200100
C        THE SIMULATION IS PERFORMED OVER A RANGE OF DIFFERENT INPUT *S2200110
C        FREQUENCIES ABOUT THE TARGET CENTER FREQUENCY OF 600 HZ. *S2200120
C        AFTER SIMULATION THE FREQUENCY RESPONSE IS PLOTTED FOR   *S2200130
C        GRAPHICAL REVIEW.                                        *S2200140
C                                                                 *S2200150
C******************************************************************S2200160
C VARIABLE DECLARATIONS                                            S2200170
      INTEGER IMOUT                                                S2200180
      REAL TX,F(9)                                                 S2200190
      REAL NUM(1024)                                               S2200200
      REAL IN(1024)                                                S2200210
      REAL OUT(1024)                                               S2200220
      REAL X1(3),X2(3),Y1(3),Y2(3)                                 S2200230
      REAL SCALS1,SCALS2,SINMAG,MOUT                               S2200240
      REAL DN213(3),DD213(3),DN223(3),DD223(3),T,PI,TWOPIF         S2200250
C INPUT FREQUENCIES                                                S2200260
      F(1)=700                                                     S2200270
C     F(2)=                                                        S2200280
C     F(3)=                                                        S2200290
C     F(4)=                                                        S2200300
C     F(5)=                                                        S2200310
C     F(6)=                                                        S2200320
C     F(7)=                                                        S2200330
C     F(8)=                                                        S2200340
C     F(9)=                                                        S2200350
      WRITE(4,80)                                                  S2200360
   80 FORMAT('FOURTH ORDER FILTER FREQUENCY RESPONSE',/,           S2200370
     &'   (CASCADED SECOND ORDER SECTIONS)',//)                    S2200380
C FIRST SECOND ORDER STAGE COEFFICIENTS                            S2200390
      DN213(3)=1.                                                  S2200400
      DN213(2)=-1.749875                                           S2200410
      DN213(1)=1.001585                                            S2200420
      DD213(3)=1.                                                  S2200430
      DD213(2)=-1.81555                                            S2200440
      DD213(1)=0.990601                                            S2200450
C PRINT FIRST STAGE TRANSFER FUNCTION                              S2200460
      WRITE(4,81)DN213(3),DN213(2),DN213(1),DD213(3),DD213(2),DD213(1) S2200470
   81 FORMAT('FIRST STAGE TRANSFER FUNCTION (2920 EQUIVALENT)',//, S2200480
     &E14.6,' + ',E14.6,' Z**-1 + ',E14.6,' Z**-2',/,             S2200490
     &' ---------------------------------------------------------',//,S2200500
     &E14.6,' + ',E14.6,' Z**-1 + ',E14.6,' Z**-2',///)           S2200510
C SECOND SECOND ORDER STAGE COEFFICIENTS                           S2200520
      DN223(3)=1.                                                  S2200530
      DN223(2)=-1.877805                                           S2200540
      DN223(1)=0.998169                                            S2200550
```

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```
        DD223(3)=1.                                                    S2200560
        DD223(2)=-1.809446                                             S2200570
        DD223(1)=0.982544                                              S2200580
C PRINT SECOND STAGE TRANSFER FUNCTION                                 S2200590
        WRITE(4,82)DN223(3),DN223(2),DN223(1),DD223(3),DD223(2),DD223(1) S2200600
     82 FORMAT('SECOND STAGE TRANSFER FUNCTION (2920 EQUIVALENT)',//,  S2200610
       &E14.6,' + ',E14.6,' Z**-1 + ',E14.6,' Z**-2',/,               S2200620
       &'  --------------------------------------------------',//,    S2200630
       &E14.6,' + ',E14.6,' Z**-1 + ',E14.6,' Z**-2',///)            S2200640
C INITIALIZE VARIABLES                                                 S2200650
        PI=3.1415927                                                   S2200660
        SCALS1=0.                                                      S2200670
        SCALS2=0.                                                      S2200680
C SAMPLE PERIOD = T = 1.1521152 X 10**-4 SECONDS                       S2200690
        T=4.*192./6.666E6                                              S2200700
C COMPUTE SCALE SUM FOR STAGES TO LIMIT INPUT AMPLITUDE                S2200710
        DO 6 K=1,3                                                     S2200720
          SCALS1=SCALS1+ABS(DN213(K))                                  S2200730
          SCALS1=SCALS1+ABS(DD213(K))                                  S2200740
          SCALS2=SCALS2+ABS(DN223(K))                                  S2200750
          SCALS2=SCALS2+ABS(DD223(K))                                  S2200760
      6 CONTINUE                                                       S2200770
C ENSURE SCALE SUM FACTORS WILL LIMIT OUTPUT TO LESS THAN ONE          S2200780
        SCALS1=SCALS1+1.E-6                                            S2200790
        SCALS2=SCALS2+1.E-6                                            S2200800
C COMPUTE SIMULATED INPUT MAGNITUDE LIMIT                              S2200810
        SINMAG=1./(SCALS1*SCALS2)                                      S2200820
C PRINT STAGE SCALE SUMS AND INPUT MAGNITUDE LIMIT                     S2200830
        WRITE(4,85)SCALS1,SCALS2,SINMAG                                S2200840
     85 FORMAT(//,'SCALE FACTORS AND INPUT MAGNITUDE LIMIT',//,       S2200850
       &'FIRST STAGE SCALE SUM = ',E14.6,/,                           S2200860
       &'SECOND STAGE SCALE SUM = ',E14.6,/,                          S2200870
       &'INPUT AMPLITUDE LIMITED TO +/- ',E14.6,///)                  S2200880
C BEGIN SIMULATION FOR SPECIFIED FREQUENCIES GIVEN BY F(L)             S2200890
C*********************************                                     S2200900
C ADJUST AS NECESSARY                                                  S2200910
        DO 20 L=1,1                                                    S2200920
C*********************************                                     S2200930
C COMPUTE SIMULATION RUN INPUT CONSTANT FOR EACH FREQUENCY             S2200940
        TWOPIF=2.*PI*F(L)                                             S2200950
C INITIALIZE STAGE INPUTS AND OUTPUTS                                  S2200960
        IMOUT=0                                                        S2200970
        MOUT=0.                                                        S2200980
        DO 5 I=1,3                                                     S2200990
          X1(I)=0.                                                     S2201000
          X2(I)=0.                                                     S2201010
          Y1(I)=0.                                                     S2201020
          Y2(I)=0.                                                     S2201030
      5   CONTINUE                                                     S2201040
C PRINT SIMULATION HEADINGS                                            S2201050
        WRITE(4,98)F(L)                                               S2201060
     98   FORMAT(///,'FILTER FREQUENCY RESPONSE FOR F = ',F5.0,' HZ',//) S2201070
        WRITE(4,99)                                                   S2201080
     99   FORMAT(/,'   I      TIME      IN1     OUT1=IN2    OUT2',//) S2201090
C COMPUTE SIMULATED FILTER RESPONSE OVER INDICATED NUMBER OF SAMPLES (I)S2201100
```

```
FILE: S22FG    FORTRAN  A1


C********************************                                S2201110
C ADJUST AS NECESSARY                                           S2201120
          DO 10 I=1,1024                                        S2201130
C********************************                                S2201140
C TX = TOTAL ELAPSED SAMPLE TIME                                S2201150
          TX=T*FLOAT(I-1)                                       S2201160
C IN1 = X1(1) = FILTER FIRST STAGE INPUT VALUE (LIMITED BY SINMAG) S2201170
          X1(1)=SINMAG*SIN(TWOPIF*TX)                           S2201180
          NUM(I)=FLOAT(I)                                       S2201190
          IN(I)=X1(1)                                           S2201200
C OUT1 = Y1(1) = FIRST STAGE OUTPUT = IN2 = X2(1) = SECOND STAGE INPUT S2201210
          Y1(1)=DN213(3)*X1(1)+DN213(2)*X1(2)+DN213(1)*X1(3)-   S2201220
     &        DD213(2)*Y1(2)-DD213(1)*Y1(3)                     S2201230
          X2(1)=Y1(1)                                           S2201240
C OUT2 = Y2(1) = SECOND STAGE OUTPUT = FILTER OUTPUT            S2201250
          Y2(1)=DN223(3)*X2(1)+DN223(2)*X2(2)+DN223(1)*X2(3)-   S2201260
     &        DD223(2)*Y2(2)-DD223(1)*Y2(3)                     S2201270
          OUT(I)=Y2(1)                                          S2201280
C PRINT PARAMETERS FOR EACH SIMULATION ITERATION                S2201290
C********************************                                S2201300
C          WRITE(4,100)I,TX,X1(1),X2(1),Y2(1)                   S2201310
C 100      FORMAT(1X,I4,2X,4(F10.3,2X))                         S2201320
C USE THIS OUTPUT FORMAT FOR EASYPLOT ROUTINE                   S2201330
C          WRITE(4,100)TX,X1(1),Y2(1)                           S2201340
C 100      FORMAT(1X,3(F15.8,2X))                               S2201350
C********************************                                S2201360
C REMEMBER MAXIMUM AMPLITUDE IN EACH FREQUENCY SIMULATION TRIAL S2201370
          IF (ABS(Y2(1))-MOUT) 11,11,14                         S2201380
     14       MOUT=ABS(Y2(1))                                   S2201390
             IMOUT=I                                            S2201400
C PERFORM SIMULATION SHIFT DELAY                                S2201410
     11      DO 15 J=2,3,1                                       S2201420
             Y1(5-J)=Y1(4-J)                                    S2201430
             X1(5-J)=X1(4-J)                                    S2201440
             Y2(5-J)=Y2(4-J)                                    S2201450
             X2(5-J)=X2(4-J)                                    S2201460
     15      CONTINUE                                           S2201470
     10   CONTINUE                                              S2201480
C PRINT MAXIMUM OUTPUT AMPLITUDE FOR EACH FREQUENCY SIMULATION RUN S2201490
        WRITE(4,89)F(L),MOUT,IMOUT                              S2201500
     89   FORMAT(' MAXIMUM OUTPUT AMPLITUDE FOR ',F5.0,' HZ = ',F15.8,/, S2201510
     &' THIS OCCURRED AT SIMULATION ITERATION ',I5)             S2201520
     20 CONTINUE                                                S2201530
C----------------------------------------------------------- S2201540
C GRAPHICS PARAMETERS FOR FREQUENCY RESPONSE OUTPUT VS INPUT    S2201550
C----------------------------------------------------------- S2201560
        CALL LRGBUF                                             S2201570
C       CALL TEK618                                             S2201580
        CALL COMPRS                                             S2201590
C .....    SETUP THE PLOTTING AREA                              S2201600
        CALL PAGE (11.0,8.5)                                    S2201610
        CALL NOBRDR                                             S2201620
        CALL AREA2D(9.0,6.5)                                    S2201630
C .....  LABEL THE X & Y AXES                                   S2201640
        CALL XNAME('ITERATION (N) $',100)                       S2201650
```

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```
      CALL YNAME('MAGNITUDE$',100)                                    S2201660
      CALL HEADIN ('DIGITAL FILTER FREQUENCY RESPONSE$',100,1.6,3)    S2201670
      CALL HEADIN ('SIMULATION INPUT/OUTPUT VS ITERATION$',100,1.,3)  S2201680
      CALL HEADIN ('FREQUENCY = 700 HZ$',100,1.,3)                    S2201690
C .....    DEFINE THE AXES                                           S2201700
      CALL GRAF(0.,64.,1024.,-2.0,.5,2.0)                             S2201710
C..... DRAW THE INPUT CURVE                                          S2201720
      CALL THKCRV(0.01)                                              S2201730
      CALL MARKER(15)                                                 S2201740
      CALL CURVE(NUM,IN,1024,0)                                       S2201750
C..... DRAW THE OUTPUT CURVE                                         S2201760
      CALL THKCRV(0.01)                                              S2201770
      CALL MARKER(15)                                                 S2201780
      CALL CURVE(NUM,OUT,1024,0)                                      S2201790
C..... TERMINATE THIS PLOT                                           S2201800
      CALL ENDPL(0)                                                   S2201810
      CALL DONEPL                                                     S2201820
      STOP                                                            S2201830
      END                                                             S2201840
```

DIGITAL FILTER FREQUENCY RESPONSE
SIMULATION INPUT/OUTPUT VS ITERATION
FREQUENCY - 500 HZ
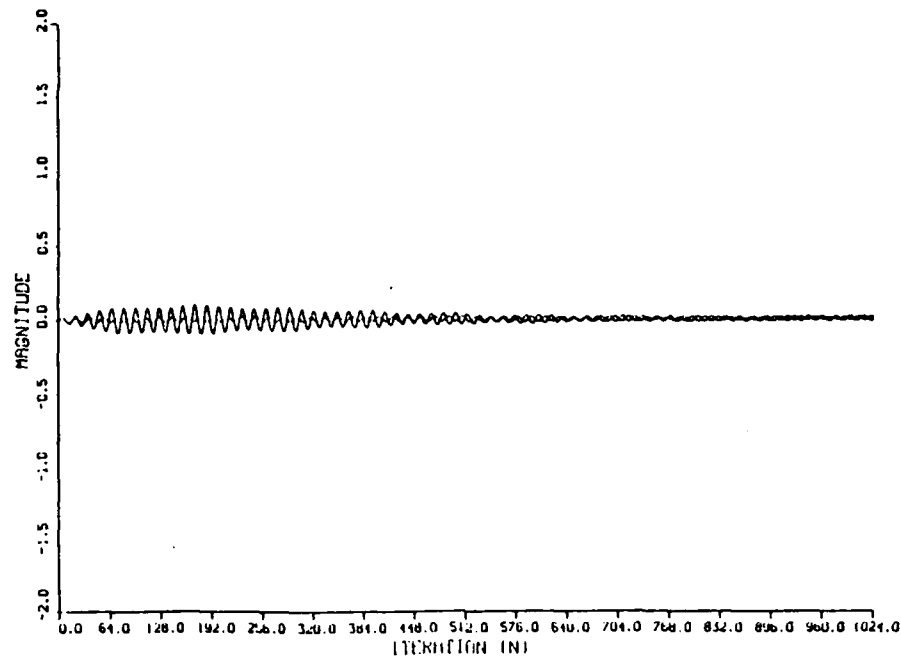
DIGITAL FILTER FREQUENCY RESPONSE
SIMULATION INPUT/OUTPUT VS ITERATION
FREQUENCY - 575 HZ

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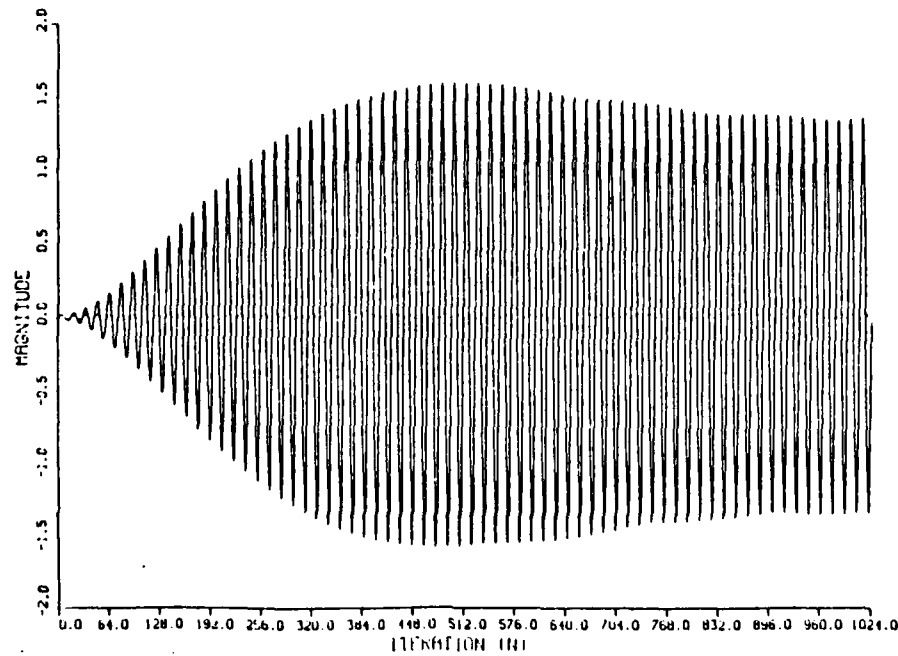
DIGITAL FILTER FREQUENCY RESPONSE
SIMULATION INPUT/OUTPUT VS ITERATION
FREQUENCY - 590.825 HZ
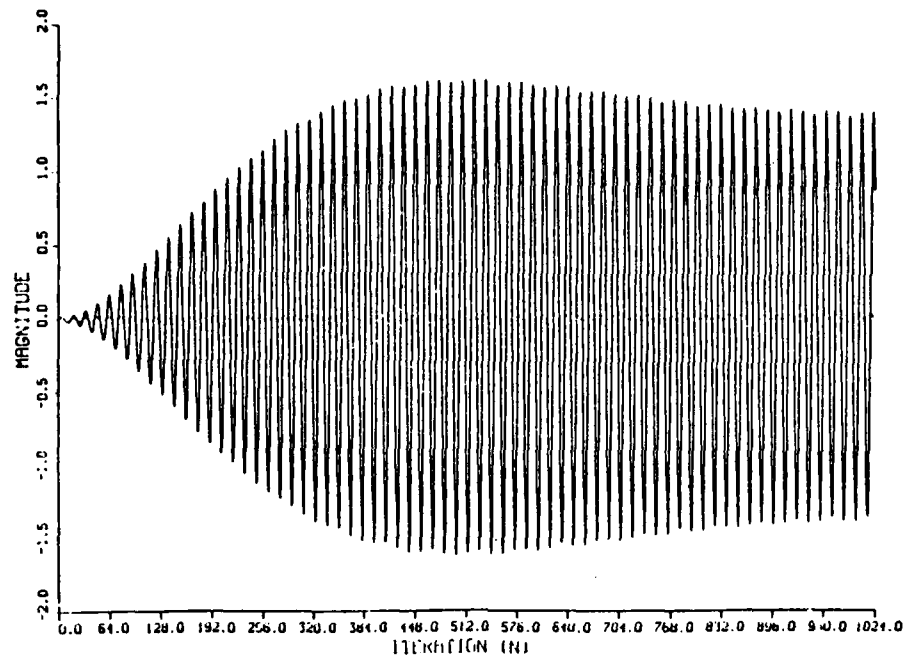
DIGITAL FILTER FREQUENCY RESPONSE
SIMULATION INPUT/OUTPUT VS ITERATION
FREQUENCY - 600 HZ

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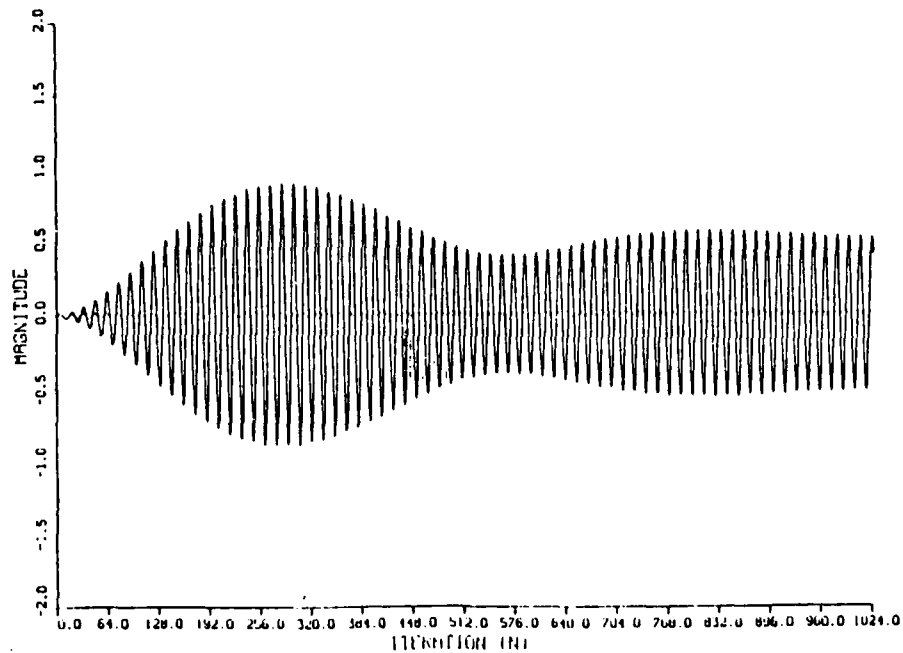
DIGITAL FILTER FREQUENCY RESPONSE
SIMULATION INPUT/OUTPUT VS ITERATION
FREQUENCY - 625 HZ
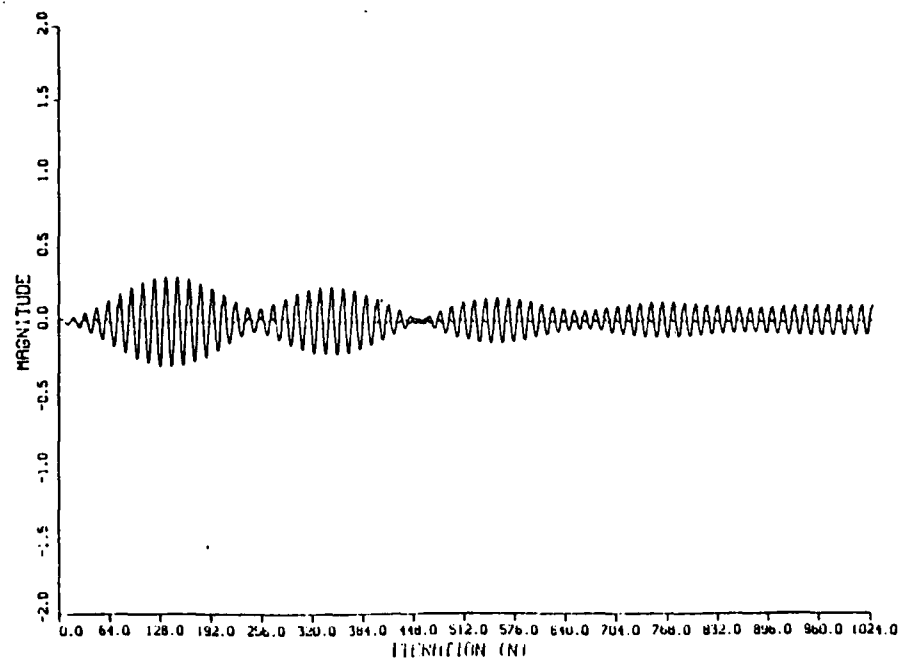
DIGITAL FILTER FREQUENCY RESPONSE
SIMULATION INPUT/OUTPUT VS ITERATION
FREQUENCY - 700 HZ
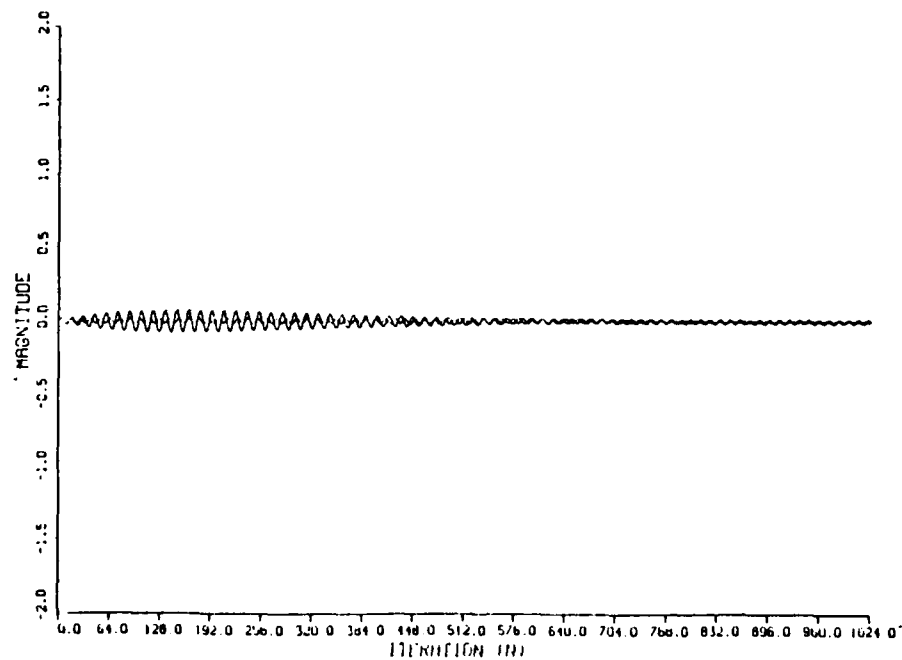
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    LINE LOC OBJECT SOURCE STATEMENT

       1   ;
       2   ;   APPENDIX H
       3   ;
       4   ; 2920 ASSEMBLY LANGUAGE PROGRAM SMS%2
       5   ; 600 HZ CENTER FREQUENCY BAND-PASS FILTER
       6   ; FOURTH ORDER ELLIPTIC FILTER
       7   ; AUTHOR: LT D. W. JORDAN
       8   ;
       9   ; CLEAR IAR REGISTER
      10   0 4006EF   LDA IAR,KP0
      11   ;
      12   ; INPUT ANALOG SAMPLE TO SAMPLE/HOLD
      13   ; INPUT MUST BE LESS THAN 1.0 VOLTS
      14   1 0000EF   IN0
      15   2 0000EF   IN0
      16   3 0000EF   IN0
      17   4 0000EF   IN0
      18   5 4000EF   NOP
      19   6 4000EF   NOP
      20   7 4000EF   NOP
      21   ;
      22   ; BEGIN ANALOG TO DIGITAL CONVERSION
      23   ; DIGITAL SAMPLE WILL RESIDE IN IAR REGISTER
      24   8 6000EF   OUT8
      25   9 4000EF   NOP
      26   10 4000EF   NOP
      27   11 4000EF   NOP
      28   12 7100EF   OUT7
      29   13 4000EF   NOP
      30   14 4000EF   NOP
      31   15 4000EF   NOP
      32   16 6100EF   OUT6
      33   17 4000EF   NOP
      34   18 4000EF   NOP
      35   19 4000EF   NOP
      36   20 5100EF   OUT5
      37   21 4000EF   NOP
      38   22 4000EF   NOP
      39   23 4000EF   NOP
      40   24 4100EF   OUT4
      41   25 4000EF   NOP
      42   26 4000EF   NOP
      43   27 4000EF   NOP
      44   28 3100EF   OUT3
      45   29 4000EF   NOP
      46   30 4000EF   NOP
      47   31 4000EF   NOP
      48   32 2100EF   OUT2
      49   33 4000EF   NOP
      50   34 4000EF   NOP
      51   35 4000EF   NOP
      52   36 1100EF   OUT1

```
LINE  LOC OBJECT SOURCE STATEMENT

  53   37 4000EF     NOP
  54   38 4000EF     NOP
  55   39 4000EF     NOP
  56   40 0100EF     CVT0
  57   41 4000EF     NOP
  58   42 4000EF     NOP
  59   43 4000EF     NOP
  60              :
  61              : SCALE DOWN DIGITAL INPUT BY A FACTOR OF 64
  62   44 406ERE     LDA IRP,IRP,R06
  63              :
  64              : LOAD SCALED INPUT FROM IRP INTO X11
  65   45 4022EF     LDA Y11,IRP
  66              :
  67              : INITIALIZE Y11
  68   46 4082FF     LDA Y11,KP0
  69              :
  70              : PERFORM FIRST STAGE DIFFERENCE EQUATION COMPUTATION
  71              : Y11=N13*X11-N12*X12+N11*X12+D12*Y12-D11*Y12
  72              :
  73              : Y11=N13*X11
  74              : (N13=1.000000)
  75              :
  76   47 4400EF     LDA PRD,X11
  77              :
  78   48 4200FD     ADD Y11,PRD
  79              :
  80              : Y11=Y11-N12*X12
  81              : (N12=1.749875)
  82              :
  83   49 4608EF     LDA PRD,X12,R00
  84   50 46090C     ADD PRD,X12,R01
  85   51 46094C     ADD PRD,X12,R03
  86   52 46096C     ADD PRD,X12,R04
  87   53 46088C     ADD PRD,X12,R05
  88   54 4608AC     ADD PRD,X12,R06
  89   55 4608CC     ADD PRD,X12,R07
  90   56 4608EC     ADD PRD,X12,R08
  91   57 46090D     ADD PRD,X12,R09
  92   58 46092D     ADD PRD,X12,P10
  93   59 46094D     ADD PRD,X12,P11
  94   60 46096D     ADD PRD,X12,P12
  95   61 46098D     ADD PRD,X12,P13
  96              :
  97   62 4200FD     SUB Y11,PRD
  98              :
  99              : Y11=Y11+N11*Y12
 100              : (N11=1.001585)
 101              :
 102   63 4C08EF     LDA PRD,X12,P00
 103   64 4C002D     ADD PRD,X12,P10
 104   65 4C004D     ADD PRD,X12,P11
 105   66 4C008D     ADD PRD,X12,P13
 106              :
```

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LINE  LOC OBJECT SOURCE STATEMENT

 107   67 4200FD     ADD Y11,FPD
 108              ;
 109              ; Y11=Y11+D12*Y12
 110              ; (D12=1.815550)
 111              ;
 112   68 4C09EF     LDA FPD,Y12,R00
 113   69 4C080C     ADD FPD,Y12,R01
 114   70 4C082C     ADD FPD,Y12,R02
 115   71 4C086C     ADD FPD,Y12,R04
 116   72 4C080D     ADD FPD,Y12,R09
 117   73 4C082D     ADD FPD,Y12,R10
 118   74 4C088D     ADD FPD,Y12,R13
 119              ;
 120   75 4200FD     ADD Y11,FPD
 121              ;
 122              ; Y11=Y11-D11*Y13
 123              ; (D11=0.990601)
 124              ;
 125   76 4E000E     LDA FPD,Y13,R01
 126   77 4E002C     ADD FPD,Y13,R02
 127   78 4E004C     ADD FPD,Y13,R03
 128   79 4E006C     ADD FPD,Y13,R04
 129   80 4E008C     ADD FPD,Y13,R05
 130   81 4E00AC     ADD FPD,Y13,R06
 131   82 4E00EC     ADD FPD,Y13,R08
 132   83 4E000D     ADD FPD,Y13,R09
 133   84 4E006D     ADD FPD,Y13,R12
 134   85 4E008D     ADD FPD,Y13,R13
 135              ;
 136   86 4200FB     SUB Y11,FPD
 137              ;
 138              ; INITIALIZE Y21
 139   87 4498FF     LDA Y21,KP0
 140              ;
 141              ; PERFORM SECOND STAGE DIFFERENCE EQUATION COMPUTATION
 142              ; Y21=N23*Y11-N22*X22+N21*X23+D22*Y22-D21*Y23
 143              ;
 144              ; Y21=N23*Y11
 145              ; (N23=1.000000)
 146              ;
 147   88 4408EF     LDA FPD,Y11
 148              ;
 149   89 4610FD     ADD Y21,FPD
 150              ;
 151              ; Y21=Y21-N22*X22
 152              ; (N22=1.877905)
 153              ;
 154   90 4420EF     LDA FPD,X22,R00
 155   91 44200C     ADD FPD,X22,R01
 156   92 44202C     ADD FPD,X22,R02
 157   93 44204C     ADD FPD,X22,R03
 158   94 44200D     ADD FPD,X22,R09
 159   95 44204D     ADD FPD,X22,R11
 160   96 44206D     ADD FPD,X22,R12
```

LINE LOC OBJECT SOURCE STATEMENT

```
161   97 44202D      ADD PPD,X22,P12
162              ;
163   98 4610FB      SUB Y21,PPD
164              ;
165              ; Y21=Y21+M21*X23
166              ; (M21=0.998169)
167              ;
168   99 44290E      LDA PPD,X23,P01
169  100 44282C      ADD PPD,X23,P02
170  101 44284C      ADD PPD,X23,P03
171  102 44286C      ADD PPD,X23,P04
172  103 44288C      ADD PPD,X23,P05
173  104 4428AC      ADD PPD,X23,P06
174  105 4428CC      ADD PPD,X23,P07
175  106 4428EC      ADD PPD,X23,P08
176  107 44290D      ADD PPD,X23,P09
177  108 44288D      ADD PPD,X23,P13
178              ;
179  109 4610FD      ADD Y21,PPD
180              ;
181              ; Y21=Y21-D22*Y22
182              ; (D22=1.809446)
183              ;
184  110 4620EF      LDA PPD,Y22,P00
185  111 46200C      ADD PPD,Y22,P01
186  112 46202C      ADD PPD,Y22,P02
187  113 46208C      ADD PPD,Y22,P05
188  114 4620AC      ADD PPD,Y22,P06
189  115 4620CC      ADD PPD,Y22,P07
190  116 4620EC      ADD PPD,Y22,P08
191  117 46204D      ADD PPD,Y22,P11
192  118 46206D      ADD PPD,Y22,P12
193  119 46208D      ADD PPD,Y22,P13
194              ;
195  120 4610FD      ADD Y21,PPD
196              ;
197              ; Y21=Y21-D21*Y23
198              ; (D21=0.962544)
199              ;
200  121 46290E      LDA PPD,Y23,P01
201  122 46282C      ADD PPD,Y23,P02
202  123 46284C      ADD PPD,Y23,P03
203  124 46286C      ADD PPD,Y23,P04
204  125 46288C      ADD PPD,Y23,P05
205  126 4628CC      ADD PPD,Y23,P07
206  127 4628EC      ADD PPD,Y23,P08
207  128 46290D      ADD PPD,Y23,P09
208  129 46288D      ADD PPD,Y23,P13
209              ;
210  130 4610FB      SUB Y21,PPD
211              ;
212              ; LOAD Y21 INTO IAR FOR OUTPUT
213  131 4A4CEF      LDA IAR,Y21,P00
214              ;
```

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A MATCHED FILTER ALGORITHM FOR ACOUSTIC SIGNAL
DETECTION(U) NAVAL POSTGRADUATE SCHOOL MONTEREY CA
D W JORDAN JUN 85

UNCLASSIFIED

F/G 17/1   NL

END

FILMED

DTIC
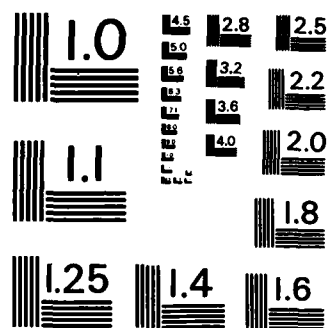
MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A

```
LINE  LOC OBJECT SOURCE STATEMENT

215                     ; MULTIPLY OUTPUT BY A FACTOR OF 4
216   132 4066AF          LDA DAR,DAR,L02
217   133 4000EF          NOP
218   134 4000EF          NOP
219   135 4000EF          NOP
220   136 4000EF          NOP
221   137 4000EF          NOP
222   138 4000EF          NOP
223                     ;
224                     ; OUTPUT VALUE IN DAR TO CHANNEL 0
225   139 8000EF          OUT0
226   140 8000EF          OUT0
227   141 8000EF          OUT0
228   142 8000EF          OUT0
229                     ;
230                     ; SERIAL REGISTER SHIFT FOR NEXT PROGRAM PASS
231   143 4660FF          LDA Y23,Y22,R00
232   144 4E48EF          LDA Y22,Y21,R00
233   145 4C18EF          LDA Y13,Y12,R00
234   146 4018FF          LDA Y12,Y11,R00
235   147 4060FF          LDA X23,X22,R00
236   148 4048EF          LDA X22,Y11,R00
237   149 4218EF          LDA X13,X12,R00
238   150 4400FF          LDA X12,X11,R00
239   151 4000EF          NOP
240   152 4000EF          NOP
241   153 4000EF          NOP
242   154 4000EF          NOP
243   155 4000EF          NOP
244   156 4000EF          NOP
245   157 4000EF          NOP
246   158 4000EF          NOP
247   159 4000EF          NOP
248   160 4000EF          NOP
249   161 4000EF          NOP
250   162 4000EF          NOP
251   163 4000EF          NOP
252   164 4000EF          NOP
253   165 4000EF          NOP
254   166 4000EF          NOP
255   167 4000EF          NOP
256   168 4000EF          NOP
257   169 4000EF          NOP
258   170 4000EF          NOP
259   171 4000EF          NOP
260   172 4000EF          NOP
261   173 4000EF          NOP
262   174 4000EF          NOP
263   175 4000EF          NOP
264   176 4000EF          NOP
265   177 4000EF          NOP
266   178 4000EF          NOP
267   179 4000EF          NOP
268   180 4000EF          NOP
```

```
LINE  LOC OBJECT SOURCE STATEMENT

269  181 4000EF     NOP
270  182 4000EF     NOP
271  183 4000EF     NOP
272  184 4000EF     NOP
273  185 4000EF     NOP
274  186 4000EF     NOP
275  187 4000EF     NOP
276              ;
277              ; THIS IS THE FINAL FOUR INSTRUCTION SEGMENT
278  188 5000EF     EOP
279  189 4000EF     NOP
280  190 4000EF     NOP
281  191 4000EF     NOP
282              END
```

SYMBOL: VALUE:

SYMBOL	VALUE
X11	0
Y11	1
PPD	2
X12	3
X13	4
Y12	5
Y13	6
Y21	7
X22	8
X23	9
Y22	10
Y23	11

```
ASSEMBLY COMPLETE
ERRORS   =     0
WARNINGS =     0
RAMSIZE  =    12
ROMSIZE  =   192
```

```
C*************************************************************************CTR00010
C                                                                         *CTR00020
C                              APPENDIX I                                  *CTR00030
C                                                                          *CTR00040
C                         FORTRAN PROGRAM CTRANS2                          *CTR00050
C                                                                          *CTR00060
C                                                                          *CTR00070
C        THIS PROGRAM PERFORMS A TRANSFORMATION OF THE COEFFICIENTS        *CTR00080
C        OF TWO SECOND ORDER POLYNOMIAL STAGES FOR 2920 IMPLEMENTATION     *CTR00090
C                                                                          *CTR00100
C*************************************************************************CTR00110
C VARIABLE DECLARATIONS                                                     CTR00120
      REAL N2(2,3),D2(2,3),N2TX,D2TX,TRIAL,TWOVAL,FKM1                      CTR00130
      REAL N2B(2,3),D2B(2,3),N2P(2,3),D2P(2,3)                              CTR00140
      INTEGER N2T(2,3,14),D2T(2,3,14)                                       CTR00150
      INTEGER JM1,JX,KM1                                                    CTR00160
C ACTUAL FIRST STAGE COEFFICIENTS TO BE TRANSFORMED                         CTR00170
 .    N2(1,3)=1.                                                            CTR00180
      N2(1,2)=-1.7499                                                       CTR00190
      N2(1,1)=1.0017                                                        CTR00200
      D2(1,3)=1.                                                            CTR00210
      D2(1,2)=-1.8156                                                       CTR00220
      D2(1,1)=0.99068                                                       CTR00230
C ACTUAL SECOND STAGE COEFFICIENTS TO BE TRANSFORMED                        CTR00240
      N2(2,3)=1.                                                            CTR00250
      N2(2,2)=-1.8779                                                       CTR00260
      N2(2,1)=0.99817                                                       CTR00270
      D2(2,3)=1.                                                            CTR00280
      D2(2,2)=-1.8095                                                       CTR00290
      D2(2,1)=0.98255                                                       CTR00300
C INITIALIZE BINARY COEFFICIENT MATRIX                                      CTR00310
      DO 10 I=1,2                                                           CTR00320
         DO 12 J=1,3                                                        CTR00330
            N2B(I,J)=0.                                                     CTR00340
            D2B(I,J)=0.                                                     CTR00350
            N2P(I,J)=0.                                                     CTR00360
            D2P(I,J)=0.                                                     CTR00370
            DO 14 K=1,13                                                    CTR00380
               N2T(I,J,K)=0                                                 CTR00390
               D2T(I,J,K)=0                                                 CTR00400
 14         CONTINUE                                                        CTR00410
 12      CONTINUE                                                           CTR00420
 10   CONTINUE                                                              CTR00430
C PERFORM COEFFICIENT TRANSFORMATION TO BINARY 2920 REPRESENTATION          CTR00440
C NUMERATOR TERMS                                                           CTR00450
      DO 20 I=1,2                                                           CTR00460
         DO 22 J=1,3                                                        CTR00470
         N2TX=ABS(N2(I,J))                                                  CTR00480
         IF (N2TX-1.0) 221,222,223                                         CTR00490
 222        N2T(I,J,1)=1                                                    CTR00500
            N2B(I,J)=1.0                                                    CTR00510
            GO TO 22                                                        CTR00520
 223        N2T(I,J,1)=1                                                    CTR00530
            N2B(I,J)=1.0                                                    CTR00540
            N2TX=N2TX-1.                                                    CTR00550
```

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```
221             DO 24 K=2,14                                   CTR00560
                FKM1=FLOAT(K-1)                                CTR00570
                TWOVAL=1./(2.**FKM1)                           CTR00580
                TRIAL=N2TX-TWOVAL                              CTR00590
                IF (TRIAL) 25,242,243                          CTR00600
242             N2T(I,J,K)=1                                   CTR00610
                N2B(I,J)=N2B(I,J)+TWOVAL                       CTR00620
                GO TO 20                                       CTR00630
243             N2T(I,J,K)=1                                   CTR00640
                N2B(I,J)=N2B(I,J)+TWOVAL                       CTR00650
                N2TX=TRIAL                                     CTR00660
                GO TO 24                                       CTR00670
25              IF (K.EQ.14) N2T(I,J,K)=0                      CTR00680
24            CONTINUE                                         CTR00690
22        CONTINUE                                             CTR00700
20  CONTINUE                                                   CTR00710
C DENOMINATOR TERMS                                            CTR00720
.   DO 30 I=1,2                                                CTR00730
        DO 32 J=1,3                                            CTR00740
          D2TX=ABS(D2(I,J))                                    CTR00750
          IF (D2TX-1.0) 321,322,323                           CTR00760
322       D2T(I,J,1)=1                                         CTR00770
          D2B(I,J)=1.0                                         CTR00780
          GO TO 32                                             CTR00790
323       D2T(I,J,1)=1                                         CTR00800
          D2B(I,J)=1.0                                         CTR00810
          D2TX=D2TX-1.                                         CTR00820
321         DO 34 K=2,14                                       CTR00830
            FKM1=FLOAT(K-1)                                    CTR00840
            TWOVAL=1./(2.**FKM1)                               CTR00850
            TRIAL=D2TX-TWOVAL                                  CTR00860
            IF (TRIAL) 35,342,343                              CTR00870
342         D2T(I,J,K)=1                                       CTR00880
            D2B(I,J)=D2B(I,J)+TWOVAL                           CTR00890
            GO TO 30                                           CTR00900
343         D2T(I,J,K)=1                                       CTR00910
            D2B(I,J)=D2B(I,J)+TWOVAL                           CTR00920
            D2TX=TRIAL                                         CTR00930
            GO TO 34                                           CTR00940
35          IF (K.EQ.14) D2T(I,J,K)=0                          CTR00950
34        CONTINUE                                             CTR00960
32      CONTINUE                                               CTR00970
30  CONTINUE                                                   CTR00980
C PRINT OUTPUT HEADING                                         CTR00990
    WRITE(4,80)                                                CTR01000
80  FORMAT(' PROGRAM CTRANS2 OUTPUT',//,                       CTR01010
   &' FOURTH ORDER DIGITAL FILTER 2920 BINARY EQUIVALENTS',/,  CTR01020
   &'   (TWO CASCADED SECOND ORDER SECTIONS)',///)             CTR01030
C PRINT FIRST STAGE TRANSFER FUNCTION                          CTR01040
    WRITE(4,81)N2(1,3),N2(1,2),N2(1,1),D2(1,3),D2(1,2),D2(1,1) CTR01050
81  FORMAT(' FIRST STAGE TRANSFER FUNCTION',//,                CTR01060
   &' ',E14.6,' + ',E14.6,' Z**-1 + ',E14.6,' Z**-2',/,        CTR01070
   &' ------------------------------------------------',//,    CTR01080
   &' ',E14.6,' + ',E14.6,' Z**-1 + ',E14.6,' Z**-2')          CTR01090
    WRITE(4,810)                                               CTR01100
```

```
810 FORMAT(///,' BINARY REPRESENTATION OF NUMERATOR COEFFICIENTS',//.   CTR01110
   &'          R00 R01 R02 R03 R04 R05 R06 R07 R08 R09 R10 R11 R12 R13'  CTR01120
   &,/)                                                                  CTR01130
      DO 811 J=1,3                                                       CTR01140
         JX=4-J                                                         CTR01150
         N2P(1,JX)=N2B(1,JX)/ABS(N2(1,JX))                             CTR01160
         WRITE(4,812)JX,N2(1,JX)                                        CTR01170
812      FORMAT(' N2(1,',I1,') = ',F9.6)                               CTR01180
         WRITE(4,814)N2T(1,JX,1),N2T(1,JX,2),N2T(1,JX,3),N2T(1,JX,4),  CTR01190
   &N2T(1,JX,5),N2T(1,JX,6),N2T(1,JX,7),N2T(1,JX,8),N2T(1,JX,9),       CTR01200
   &N2T(1,JX,10),N2T(1,JX,11),N2T(1,JX,12),N2T(1,JX,13),N2T(1,JX,14),  CTR01210
   &N2B(1,JX),N2P(1,JX)                                                CTR01220
814      FORMAT(9X,14(I1,3X),/,' ABSOLUTE BINARY EQUIVALENT = '        CTR01230
   &,F9.6,/,' (THIS IS ',F9.6,' OF THE ACTUAL VALUE)',/)              CTR01240
811 CONTINUE                                                           CTR01250
    WRITE(4,815)                                                       CTR01260
815 FORMAT(//,' BINARY REPRESENTATION OF DENOMINATOR COEFFICIENTS',//,CTR01270
   &'          R00 R01 R02 R03 R04 R05 R06 R07 R08 R09 R10 R11 R12 R13' CTR01280
   &,/)                                                                CTR01290
      DO 816 J=1,3                                                     CTR01300
         JX=4-J                                                        CTR01310
         D2P(1,JX)=D2B(1,JX)/ABS(D2(1,JX))                            CTR01320
         WRITE(4,817)JX,D2(1,JX)                                       CTR01330
817      FORMAT(' D2(1,',I1,') = ',F9.6)                              CTR01340
         WRITE(4,819)D2T(1,JX,1),D2T(1,JX,2),D2T(1,JX,3),D2T(1,JX,4), CTR01350
   &D2T(1,JX,5),D2T(1,JX,6),D2T(1,JX,7),D2T(1,JX,8),D2T(1,JX,9),      CTR01360
   &D2T(1,JX,10),D2T(1,JX,11),D2T(1,JX,12),D2T(1,JX,13),D2T(1,JX,14), CTR01370
   &D2B(1,JX),D2P(1,JX)                                               CTR01380
819      FORMAT(9X,14(I1,3X),/,' ABSOLUTE BINARY EQUIVALENT = '       CTR01390
   &,F9.6,/,' (THIS IS ',F9.6,' OF THE ACTUAL VALUE)',//)            CTR01400
816 CONTINUE                                                          CTR01410
C PRINT SECOND STAGE TRANSFER FUNCTION                                CTR01420
    WRITE(4,82)N2(2,3),N2(2,2),N2(2,1),D2(2,3),D2(2,2),D2(2,1)        CTR01430
82 FORMAT('1',' SECOND STAGE TRANSFER FUNCTION',//,                  CTR01440
   &E14.6,' + ',E14.6,' Z**-1 + ',E14.6,' Z**-2',//,                 CTR01450
   &'  ----------------------------------------------------',//,     CTR01460
   &E14.6,' + ',E14.6,' Z**-1 + ',E14.6,' Z**-2')                    CTR01470
    WRITE(4,820)                                                      CTR01480
820 FORMAT(//,' BINARY REPRESENTATION OF NUMERATOR COEFFICIENTS',//, CTR01490
   &'          R00 R01 R02 R03 R04 R05 R06 R07 R08 R09 R10 R11 R12 R13' CTR01500
   &,/)                                                               CTR01510
      DO 821 J=1,3                                                    CTR01520
         JX=4-J                                                       CTR01530
         N2P(2,JX)=N2B(2,JX)/ABS(N2(2,JX))                           CTR01540
         WRITE(4,822)JX,N2(1,JX)                                      CTR01550
822      FORMAT(' N2(2,',I1,') = ',F9.6)                             CTR01560
         WRITE(4,824)N2T(2,JX,1),N2T(2,JX,2),N2T(2,JX,3),N2T(2,JX,4), CTR01570
   &N2T(2,JX,5),N2T(2,JX,6),N2T(2,JX,7),N2T(2,JX,8),N2T(2,JX,9),     CTR01580
   &N2T(2,JX,10),N2T(2,JX,11),N2T(2,JX,12),N2T(2,JX,13),N2T(2,JX,14),CTR01590
   &N2B(2,JX),N2P(2,JX)                                              CTR01600
824      FORMAT(9X,14(I1,3X),/,' ABSOLUTE BINARY EQUIVALENT = '      CTR01610
   &,F9.6,/,' (THIS IS ',F9.6,' OF THE ACTUAL VALUE)',//)           CTR01620
821 CONTINUE                                                         CTR01630
    WRITE(4,825)                                                     CTR01640
825 FORMAT(/,' BINARY REPRESENTATION OF DENOMINATOR COEFFICIENTS',//,CTR01650
```

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```
     &'         R00 R01 R02 R03 R04 R05 R06 R07 R08 R09 R10 R11 R12 R13' CTR01660
     &,/)                                                                 CTR01670
       DO 826 J=1,3                                                       CTR01680
          JX=4-J                                                         CTR01690
          D2P(2,JX)=D2B(2,JX)/ABS(D2(2,JX))                             CTR01700
          WRITE(4,827)JX,D2(2,JX)                                        CTR01710
827       FORMAT(' D2(2,',I1,') = ',F9.6)                               CTR01720
          WRITE(4,829)D2T(2,JX,1),D2T(2,JX,2),D2T(2,JX,3),D2T(2,JX,4),  CTR01730
     &D2T(2,JX,5),D2T(2,JX,6),D2T(2,JX,7),D2T(2,JX,8),D2T(2,JX,9),       CTR01740
     &D2T(2,JX,10),D2T(2,JX,11),D2T(2,JX,12),D2T(2,JX,13),D2T(2,JX,14),  CTR01750
     &D2B(2,JX),D2P(2,JX)                                                CTR01760
829       FORMAT(9X,14(I1,3X),/,' ABSOLUTE BINARY EQUIVALENT = '         CTR01770
     &,F9.6,/,' (THIS IS ',F9.6,' OF THE ACTUAL VALUE)',//)             CTR01780
826    CONTINUE                                                          CTR01790
       STOP                                                              CTR01800
       END                                                               CTR01810
```

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PROGRAM CTRANS2 OUTPUT

FOURTH ORDER DIGITAL FILTER 2920 BINARY EQUIVALENTS
  (TWO CASCADED SECOND ORDER SECTIONS)

FIRST STAGE TRANSFER FUNCTION

   $0.100000E+01 + -0.174990E+01 Z^{**}-1 + 0.100170E+01 Z^{**}-2$

   $0.100000E+01 + -0.181560E+01 Z^{**}-1 + 0.990680E+00 Z^{**}-2$

BINARY REPRESENTATION OF NUMERATOR COEFFICIENTS

        R00 R01 R02 R03 R04 R05 R06 R07 R08 R09 R10 R11 R12 R13

N2(-1,3) =   1.000000
        1   0   0   0   0   0   0   0   0   0   0   0   0   0
ABSOLUTE BINARY EQUIVALENT = 1.000000
(THIS IS 1.000000 OF THE ACTUAL VALUE)

N2(1,2) = -1.749900
        1   1   0   1   1   1   1   1   1   1   1   1   1   ·1
ABSOLUTE BINARY EQUIVALENT = 1.749875
(THIS IS 0.999986 OF THE ACTUAL VALUE)

N2(1,1) =   1.001700
        1   0   0   0   0   0   0   0   0   0   1   1   0   1
ABSOLUTE BINARY EQUIVALENT = 1.001585
(THIS IS 0.999885 OF THE ACTUAL VALUE)

BINARY REPRESENTATION OF DENOMINATOR COEFFICIENTS

        R00 R01 R02 R03 R04 R05 R06 R07 R08 R09 R10 R11 R12 R13

D2(1,3) =   1.000000
        1   0   0   0   0   0   0   0   0   0   0   0   0   0
ABSOLUTE BINARY EQUIVALENT = 1.000000
(THIS IS 1.000000 OF THE ACTUAL VALUE)

D2(1,2) = -1.815600
        1   1   1   0   1   0   0   0   0   1   1   0   0   1
ABSOLUTE BINARY EQUIVALENT = 1.815550
(THIS IS 0.999972 OF THE ACTUAL VALUE)

D2(1,1) =   0.990680
        0   1   1   1   1   1   1   0   1   1   0   0   1   1
ABSOLUTE BINARY EQUIVALENT = 0.990601
(THIS IS 0.999920 OF THE ACTUAL VALUE)

SECOND STAGE TRANSFER FUNCTION

$$\frac{0.100000E+01 + -0.187790E+01 \ Z**-1 + 0.998170E+00 \ Z**-2}{0.100000E+01 + -0.180950E+01 \ Z**-1 + 0.982550E+00 \ Z**-2}$$

BINARY REPRESENTATION OF NUMERATOR COEFFICIENTS

R00 R01 R02 RC3 R04 R05 R06 R07 R08 R09 R10 R11 R12 R13

N2(2,3) = 1.000000
         1   0   0   0   0   0   0   0   0   0   0   0   0   0
ABSOLUTE BINARY EQUIVALENT = 1.000000
(THIS IS 1.000000 OF THE ACTUAL VALUE)

N2(2,2) = -1.749900
         1   1   1   1   0   0   0   0   0   1   0   1   1   1
ABSOLUTE BINARY EQUIVALENT = 1.877805
(THIS IS 0.999949 OF THE ACTUAL VALUE)

N2(2,1) = 1.001700
         0   1   1   1   1   1   1   1   1   1   0   0   0   1
ABSOLUTE BINARY EQUIVALENT = 0.998169
(THIS IS 0.999999 OF THE ACTUAL VALUE)

BINARY REPRESENTATION OF DENOMINATOR COEFFICIENTS

R00 R01 R02 R03 R04 R05 R06 R07 R08 R09 R10 R11 R12 R13

D2(2,3) = 1.000000
         1   0   0   0   0   0   0   0   0   0   0   0   0   0
ABSOLUTE BINARY EQUIVALENT = 1.000000
(THIS IS 1.000000 OF THE ACTUAL VALUE)

D2(2,2) = -1.809500
         1   1   1   0   0   1   1   1   1   0   0   1   1   1
ABSOLUTE BINARY EQUIVALENT = 1.809446
(THIS IS 0.999970 OF THE ACTUAL VALUE)

D2(2,1) = 0.982550
         0   1   1   1   1   1   0   1   1   1   0   0   0   1
ABSOLUTE BINARY EQUIVALENT = 0.982544
(THIS IS 0.999994 OF THE ACTUAL VALUE)

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C********************************************************************FIR00010
C                                                                  *FIR00020
C                          APPENDIX J                              *FIR00030
C                                                                  *FIR00040
C                     FORTRAN PROGRAM FIR4                         *FIR00050
C                   ADAPTIVE TRANSVERSAL FILTER                    *FIR00060
C                                                                  *FIR00070
C   THIS PROGRAM WILL OBTAIN THE OPTIMAL FILTER WEIGHTS FOR THE FIR *FIR00080
C   FILTER OF ORDER FOUR.   THE ALGORITHM BEGINS WITH A TRIAL REGION*FIR00090
C   (-40,40) FOR EACH OF THE WEIGHTS AND DOES A SUCCESSIVE ITERATION*FIR00100
C   OF THE ERROR FUNCTION WHILE TRANSFORMING THE WEIGHTS TO OPTIMAL *FIR00110
C   VALUES.   WHEN THE WEIGHTS CONVERGE TO OPTIMAL VALUES THEN THE  *FIR00120
C   ITERATION STOPS.   THEN WE MAY TEST THE ADEQUACY OF THE WEIGHTS *FIR00130
C   SO OBTAINED THROUGH SUBSEQUENT SIMULATION IN THE FORTRAN PROGRAM*FIR00140
C   FIR4SIM WHICH FOLLOWS AS APPPENDIX K.                          *FIR00150
C                                                                  *FIR00160
C********************************************************************FIR00170
      REAL WS(4),WU(4),WL(4),R,JE                                   FIR00180
      INTEGER NTA,NPR,NAV,NV,IP                                     FIR00190
C   WS(I) IS THE STARTING GUESS                                     FIR00200
      WS(1)=.1                                                      FIR00210
      WS(2)=1.                                                      FIR00220
      WS(3)=1.                                                      FIR00230
      WS(4)=1.                                                      FIR00240
C   WL(I) IS THE LOWER LIMIT FOR THE I'TH VARIABLE                  FIR00250
C   WU(I) IS THE UPPER LIMIT FOR THE I'TH VARIABLE                  FIR00260
      WL(1)=-14.                                                    FIR00270
      WU(1)=14.                                                     FIR00280
      WL(2)=-14.                                                    FIR00290
      WU(2)=14.                                                     FIR00300
      WL(3)=-14.                                                    FIR00310
      WU(3)=14.                                                     FIR00320
      WL(4)=-14.                                                    FIR00330
      WU(4)=14.                                                     FIR00340
C   A DESCRIPTION OF THE FOLLOWING PARAMETERS IS DISCUSSED IN BOXPLX FIR00350
      R=9./13.                                                      FIR00360
      NTA=1400                                                      FIR00370
      NPR=100                                                       FIR00380
      NAV=0                                                         FIR00390
      NV=4                                                          FIR00400
      IP=0                                                          FIR00410
C   PERFORM ITERATION ROUTINE FOR WEIGHT OPTIMIZATION               FIR00420
      CALL BOXPLX(NV,NAV,NPR,NTA,R,WS,IP,WU,WL,YMN,IER)             FIR00430
      WRITE (6,25)                                                  FIR00440
25    FORMAT(1X,' OPTIMAL GAINS',/)                                 FIR00450
      DO 30 I=1,4                                                   FIR00460
30       WRITE(6,40)I,WS(I)                                         FIR00470
40    FORMAT(1X,'W(',I2,')=',F14.7)                                 FIR00480
      STOP                                                          FIR00490
      END                                                           FIR00500
C********************************************************************FIR00510
      SUBROUTINE FIR(XX)                                            FIR00520
C   SUBROUTINE FIR(XX) SIMULATES THE FIR FILTER                     FIR00530
      COMMON J                                                      FIR00540
      REAL*8 J,W0,W1,W2,W3,X1,X2,X3,INPUT,OUTPUT                    FIR00550
```

```
          DIMENSION XX(4),DESIRE(105)                            FIR00560
C  INITIAL CONDITIONS                                            FIR00570
          ETIME=100.                                             FIR00580
          T=0.0                                                  FIR00590
          ICOUNT=2                                               FIR00600
C  INITIALIZE THE COST (CUMULATIVE ERROR) FUNCTION               FIR00610
          J=0.0                                                  FIR00620
C  GAIN COEFFICIENTS TO BE OPTIMIZED                             FIR00630
          W0=XX(1)                                               FIR00640
          W1=XX(2)                                               FIR00650
          W2=XX(3)                                               FIR00660
          W3=XX(4)                                               FIR00670
C  SHIFT REGISTERS                                               FIR00680
          X1=0.0                                                 FIR00690
          X2=0.0                                                 FIR00700
          X3=0.0                                                 FIR00710
C  SIMULATE DESIRED OUTPUT SIGNAL                                FIR00720
     .    DO 15 I=1,105                                          FIR00730
15            DESIRE(I)=-1.0                                     FIR00740
          DO 16 I=1,11                                           FIR00750
16            DESIRE(I+44)=1.0                                   FIR00760
C                                                                FIR00770
          K=1                                                    FIR00780
C  OUTPUT HEADING                                                FIR00790
C     WRITE(6,99)                                                FIR00800
C  99 FORMAT(' ','FIR TRANSVERSAL FILTER SIMULATION RESULTS',///, FIR00810
C     &' TIME        INPUT        SIMULATED OUTPUT     DESIRED OUTPUT',/) FIR00820
C  LOOP FOR 100 SAMPLE ITERATIONS                                FIR00830
    200 CONTINUE                                                 FIR00840
C  SIMULATED INPUT SIGNAL                                        FIR00850
          INPUT=SIN(.1*T)*COS(.1*T)*(2.+COS(.1*T))               FIR00860
C         INPUT=-.0004*T**2+.04*T                                FIR00870
C  SIMULATED OUTPUT SIGNAL FROM FIR FILTER                       FIR00880
          OUTPUT=W0*INPUT+W1*X1+W2*X2+W3*X3                      FIR00890
C  WHEN TO PRINTOUT                                              FIR00900
          IF (ICOUNT.EQ.2) GO TO 50                              FIR00910
          GO TO 300                                              FIR00920
C  PRINTOUT                                                      FIR00930
    50 CONTINUE                                                  FIR00940
C  EASYPLOT OUTPUT OPTION                                        FIR00950
C     WRITE (6,100) T,INPUT,OUTPUT,DESIRE(K)                     FIR00960
C 100 FORMAT(2X,F8.4,1X,F8.4,1X,F8.4,13X,F8.4)                   FIR00970
C  SCREEN OUTPUT OPTION                                          FIR00980
C     WRITE (6,100) T,INPUT,OUTPUT,DESIRE(K)                     FIR00990
C 100 FORMAT(1X,'TIME=',F8.4,5X,'INPUT=',F8.4,5X,'OUTPUT=',F8.4,5X, FIR01000
C     &'DESIRED OUTPUT=',F8.4)                                   FIR01010
          ICOUNT=1                                               FIR01020
C  TEST IF WANT TO STOP                                          FIR01030
    300 IF (T.GE.ETIME) GO TO 400                                FIR01040
C  JE=ERROR FUNCTION                                             FIR01050
          JE=(OUTPUT-DESIRE(K))**2                               FIR01060
C  J=COST FUNCTION (CUMULATIVE ERROR)                            FIR01070
          J=J+JE                                                 FIR01080
C  STEP SIZE DELT                                                FIR01090
          DELT=1.0                                               FIR01100
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        T=T+DELT                                                   FIR01110
        K=K+1                                                      FIR01120
        ICOUNT=ICOUNT+1                                            FIR01130
        X3=X2                                                      FIR01140
        X2=X1                                                      FIR01150
        X1=INPUT                                                   FIR01160
        GO TO 200                                                  FIR01170
C   OUTPUT OPTIMAL WEIGHTS                                         FIR01180
  400   WRITE(6,500) JE,W0,W1,W2,W3                                FIR01190
  500   FORMAT(' ',1X,'  J =',E15.9,2X,                           FIR01200
     1 'W0=',F15.7,2X,'W1=',F15.7,2X,'W2=',F15.7,2X,'W3=',F15.7)   FIR01210
        RETURN                                                     FIR01220
        FND                                                        FIR01230
C       ...............................................FIR01240
C                                                                  FIR01250
C       SUBROUTINE BOXPLX              (CATEGORY HO)               FIR01260
C                                                                  FIR01270
C   .   PURPOSE                                                    FIR01280
C                                                                  FIR01290
C          BOXPLX IS A SUBROUTINE USED TO SOLVE THE PROBLEM OF LOCATING  FIR01300
C          A MINIMUM (OR MAXIMUM) OF AN ARBITRARY OBJECTIVE FUNCTION     FIR01310
C          SUBJECT TO ARBITRARY EXPLICIT AND/OR IMPLICIT CONSTRAINTS BY  FIR01320
C          THE COMPLEX METHOD OF M.J. BOX.   EXPLICIT CONSTRAINTS ARE    FIR01330
C          DEFINED AS UPPER AND LOWER BOUNDS ON THE INDEPENDENT VARIABLES.FIR01340
C          IMPLICIT CONSTRAINTS MAY BE ARBITRARY FUNCTIONS OF THE VAR-   FIR01350
C          IABLES.   TWO FUNCTION SUBPROGRAMS TO EVALUATE THE OBJECTIVE  FIR01360
C          FUNCTION AND IMPLICIT CONSTRAINTS, RESPECTIVELY, MUST BE      FIR01370
C          SUPPLIED BY THE USER (SEE EXAMPLE BELOW).   BOXPLX ALSO HAS   FIR01380
C          THE OPTION TO PERFORM INTEGER PROGRAMMING, WHERE THE VALUES   FIR01390
C          OF THE INDEPENDENT VARIABLES ARE RESTRICTED TO INTEGERS.      FIR01400
C                                                                  FIR01410
C       USAGE                                                      FIR01420
C                                                                  FIR01430
C          CALL BOXPLX (NV,NAV,NPR,NTA,R,XS,IP,XU,XL,YMN,IER)      FIR01440
C                                                                  FIR01450
C                                                                  FIR01460
C       DESCRIPTION OF PARAMETERS                                  FIR01470
C                                                                  FIR01480
C          NV   AN INTEGER INPUT DEFINING THE NUMBER OF INDEPENDENT      FIR01490
C               VARIABLES OF THE OBJECTIVE FUNCTION TO BE MINIMIZED.     FIR01500
C               NOTE:   MAXIMUM NV + NAV IS PRESENTLY 50.   MAXIMIM NV IS FIR01510
C               25.   IF THESE LIMITS MUST BE EXCEEDED, PUNCH A SOURCE   FIR01520
C               DECK IN THE USUAL MANNER, AND CHANGE THE DIMENSION       FIR01530
C               STATEMENTS.                                        FIR01540
C                                                                  FIR01550
C          NAV  AN INTEGER INPUT DEFINING THE NUMBER OF AUXILIARY VAR-   FIR01560
C               IABLES THE USER WISHES TO DEFINE FOR HIS OWN CONVENIENCE. FIR01570
C               TYPICALLY HE MAY WISH TO DEFINE THE VALUE OF EACH IMPLICITFIR01580
C               CONSTRAINT FUNCTION AS AN AUXILIARY VARIABLE.   IF THIS  FIR01590
C               IS DONE, THE OPTIONAL OUTPUT FEATURE OF BOXPLX CAN BE    FIR01600
C               USED TO OBSERVE THE VALUES OF THOSE CONSTRAINTS AS THE   FIR01610
C               SOLUTION PROGRESSES.   AUXILIARY VARIABLES, IF USED,     FIR01620
C               SHOULD BE EVALUATED IN FUNCTION KE (DEFINED BELOW).      FIR01630
C               NAV MAY BE ZERO.                                   FIR01640
C                                                                  FIR01650
```

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C          NPR   INPUT INTEGER CONTROLLING THE FREQUENCY OF OUTPUT DESIRED FIR01660
C                FOR DIAGNOSTIC PURPOSES.  IF NPR .LE. 0, NO OUTPUT WILL BEFIR01670
C                PRODUCED BY BOXPLX.  OTHERWISE, THE CURRENT COMPLEX OF     FIR01680
C                K= 2*NV VERTICES AND THEIR CENTROID WILL BE OUTPUT AFTER   FIR01690
C                EACH NPR PERMISSIBLE TRIALS.  THE NUMBER OF TOTAL TRIALS,  FIR01700
C                NUMBER OF FEASIBLE TRIALS, NUMBER OF FUNCTION EVALUATIONS  FIR01710
C                AND NUMBER OF IMPLICIT CONSTRAINT EVALUATIONS ARE IN-      FIR01720
C                CLUDED IN THE OUTPUT.                                      FIR01730
C                ADDITIONALLY, (WHEN NPR .GT. 0) THE SAME INFORMATION       FIR01740
C                WILL BE OUTPUT:                                            FIR01750
C                                                                          FIR01760
C                  1) IF THE INITIAL POINT IS NOT FEASIBLE,                 FIR01770
C                  2) AFTER THE FIRST COMPLETE COMPLEX IS GENERATED,        FIR01780
C                  3) IF A FEASIBLE VERTEX CANNOT BE FOUND AT SOME TRIAL,   FIR01790
C                  4) IF THE OBJECTIVE.VALUE OF A VERTEX CANNOT BE MADE     FIR01800
C                     NO-LONGER-WORST.                                      FIR01810
C                  5) IF THE LIMIT ON TRIALS (NTA) IS REACHED AND,          FIR01820
C  .               6) WHEN THE OBJECTIVE FUNCTION HAS BEEN UNCHANGED FOR    FIR01830
C                     2*NV TRIALS, INDICATING A LOCAL MINIMUM HAS BEEN      FIR01840
C                     FOUND.                                                FIR01850
C                                                                          FIR01860
C                IF THE USER WISHES TO TRACE THE PROGRESS OF A SOLUTION,    FIR01870
C                A CHOICE OF NPR = 25, 50 OR 100 IS RECOMMENDED.            FIR01880
C                                                                          FIR01890
C          NTA   INTEGER INPUT OF LIMIT ON THE NUMBER OF TRIALS ALLOWED     FIR01900
C                IN THE CALCULATION.  IF THE USER INPUTS NTA .LE. 0, A      FIR01910
C                DEFAULT VALUE OF 2000 IS USED.  WHEN THIS LIMIT IS REACHEDFIR01920
C                CONTROL RETURNS TO THE CALLING PROGRAM WITH THE BEST       FIR01930
C                ATTAINED OBJECTIVE FUNCTION VALUE IN YMN, AND THE BEST     FIR01940
C                ATTAINED SOLUTION POINT IN XS.                            FIR01950
C                                                                          FIR01960
C          R     A REAL NUMBER INPUT TO DEFINE THE FIRST RANDOM NUMBER      FIR01970
C                USED IN DEVELOPING THE INITIAL COMPLEX OF 2*NV VERTICIES.  FIR01980
C                (0. .GT. R .LT. 1.) IF R IS NOT WITHIN THESE BOUNDS,       FIR01990
C                IT WILL BE REPLACED BY 1./3. .                            FIR02000
C                                                                          FIR02010
C          XS    INPUT REAL ARRAY DIMENSIONED AT LEAST NV+NAV. THE FIRST    FIR02020
C                NV MUST CONTAIN A FEASIBLE ORIGIN FOR STARTING THE CAL-    FIR02030
C                CULATION.  THE LAST NAV NEED NOT BE INITIALIZED.  UPON     FIR02040
C                RETURN FROM BOXPLX, THE FIRST NV ELEMENTS OF THE ARRAY     FIR02050
C                CONTAIN THE COORDINATES OF THE MINIMUM OBJECTIVE FUNCTION,FIR02060
C                AND THE REMAINING NAV (NAV .GE. 0) CONTAIN THE VALUES OF   FIR02070
C                THE CORRESPONDING AUXILIARY VARIABLES.                     FIR02080
C                                                                          FIR02090
C          IP    INTEGER INPUT FOR OPTIONAL INTEGER PROGRAMMING.  IF IP=1,  FIR02100
C                THE VALUES OF THE INDEPENDENT VARIABLES WILL BE REPLACED   FIR02110
C                WITH INTEGER VALUES (STILL STORED AS REAL*4).             FIR02120
C                                                                          FIR02130
C          XU    A REAL ARRAY DIMENSIONED AT LEAST NV INPUTTING THE UPPER   FIR02140
C                BOUND ON EACH INDEPENDENT VARIABLE, (EACH EXPLICIT CON-    FIR02150
C                STRAINT).  INPUT VALUES ARE SLIGHTLY ALTERED BY BOXPLX.    FIR02160
C                                                                          FIR02170
C          XL    A REAL ARRAY DIMENSIONED AT LEAST NV INPUTTING THE LOWER   FIR02180
C                BOUND ON EACH INDEPENDENT VARIABLE, (EACH EXPLICIT CON-    FIR02190
C                STRAINT).  NOTE:  FOR BOTH XU AND XL CHOOSE REASONABLE     FIR02200
```

```
        K=1                                                       FIR00560
C  OUTPUT HEADING                                                 FIR00570
        WRITE(6,99)                                               FIR00580
     99 FORMAT(' ','FIR TRANSVERSAL FILTER SIMULATION RESULTS',///, FIR00590
       &' TIME     INPUT      SIMULATED OUTPUT      DESIRED OUTPUT',/) FIR00600
C  LOOP FOR 100 SAMPLE ITERATIONS                                 FIR00610
    200 CONTINUE                                                  FIR00620
C  SIMULATED INPUT SIGNAL (600 HZ + 1200 HZ + 1800 HZ)           FIR00630
        INPUT=SIN(.1*T)*COS(.1*T)*(2.+COS(.1*T))                  FIR00640
C  SIMULATED OUTPUT SIGNAL FROM FIR FILTER                       FIR00650
        OUTPUT=WO*INPUT+W1*X1+W2*X2+W3*X3                         FIR00660
C  WHEN TO PRINTOUT                                               FIR00670
        IF (ICOUNT.EQ. 2) GO TO 50                               FIR00680
        GO TO 300                                                 FIR00690
C  PRINTOUT                                                       FIR00700
     50 CONTINUE                                                  FIR00710
C  EASYPLOT OUTPUT OPTION                                         FIR00720
   .    WRITE (6,100) T,INPUT,OUTPUT,DESIRE(K)                    FIR00730
    100 FORMAT(2X,F8.4,1X,F8.4,3X,F8.4,13X,F8.4)                  FIR00740
C  SCREEN OUTPUT OPTION                                           FIR00750
C       WRITE (6,100) T,INPUT,OUTPUT,DESIRE(K)                    FIR00760
C 100 FORMAT(1X,'TIME=',F7.3,5X,'INPUT=',F8.4,5X,'OUTPUT=',F8.4,5X, FIR00770
C      &'DESIRED OUTPUT=',F8.4)                                   FIR00780
        ICOUNT=1                                                  FIR00790
C  TEST IF WANT TO STOP                                           FIR00800
    300 IF (T.GE.ETIME) GO TO 400                                 FIR00810
C  JE=ERROR FUNCTION                                              FIR00820
        JE=(OUTPUT-DESIRE(K))**2                                  FIR00830
C  J=COST FUNCTION (CUMULATIVE ERROR)                             FIR00840
        J=J+JE                                                    FIR00850
C  STEP SIZE DELT                                                 FIR00860
        DELT=1.0                                                  FIR00870
        T=T+DELT                                                  FIR00880
        K=K+1                                                     FIR00890
        ICOUNT=ICOUNT+1                                           FIR00900
        X3=X2                                                     FIR00910
        X2=X1                                                     FIR00920
        X1=INPUT                                                  FIR00930
        GO TO 200                                                 FIR00940
    400 RETURN                                                    FIR00950
        END                                                       FIR00960
```

```
C************************************************************************FIR00010
C                                                                      *FIR00020
C                              APPENDIX K                              *FIR00030
C                                                                      *FIR00040
C                        FORTRAN PROGRAM FIR4SIM                       *FIR00050
C                  ADAPTIVE TRANSVERSAL FILTER SIMULATION              *FIR00060
C                                                                      *FIR00070
C  TO PERFORM THE SIMULATION WE EMPLOY THE PROGRAM FIR WHICH           *FIR00080
C  WAS USED BY FIR4 TO CALCULATE THE FILTER OUTPUT VALUES WHEN         *FIR00090
C  CALCULATING THE OPTIMAL FILTER WEIGHTS.  WE ACCOMPLISH THIS         *FIR00100
C  BY CHANGING WS(*) TO THE ACTUAL W(*) AND ALSO DELETING THE          *FIR00110
C  INITIAL TRIAL BOUNDS REPRESENTED BY WU(*) AND WL(*).                *FIR00120
C                                                                      *FIR00130
C************************************************************************FIR00140
      REAL W(4),R,JE                                                    FIR00150
C W(I) IS THE CALCULATED OPTIMAL GAIN                                   FIR00160
      W(1)=-7.5060358                                                   FIR00170
    ' W(2)=7.5403662                                                    FIR00180
      W(3)=4.7097464                                                    FIR00190
      W(4)=-5.3987589                                                   FIR00200
      WRITE (6,25)                                                      FIR00210
25    FORMAT(1X,' OPTIMAL GAINS',//)                                    FIR00220
      DO 30 I=1,4                                                       FIR00230
30        WRITE(6,40)I,W(I)                                            FIR00240
40    FORMAT(1X,'W(',I2,')=',F14.7)                                     FIR00250
      CALL FIR(W)                                                       FIR00260
      STOP                                                              FIR00270
      END                                                              FIR00280
C************************************************************************FIR00290
      SUBROUTINE FIR(XX)                                                FIR00300
C SUBROUTINE FIR(XX) SIMULATES THE FIR ADAPTIVE TRANSVERSAL FILTER      FIR00310
      COMMON J                                                          FIR00320
      REAL*8 J,W0,W1,W2,W3,X1,X2,X3,INPUT,OUTPUT                        FIR00330
      DIMENSION XX(4),DESIRE(105)                                       FIR00340
C INITIAL CONDITIONS                                                    FIR00350
      ETIME=100.                                                        FIR00360
      T=0.0                                                             FIR00370
      ICOUNT=2                                                          FIR00380
C INITIALIZE THE COST (CUMULATIVE ERROR) FUNCTION                       FIR00390
      J=0.0                                                             FIR00400
C GAIN COEFFICIENTS TO BE OPTIMIZED                                     FIR00410
      W0=XX(1)                                                          FIR00420
      W1=XX(2)                                                          FIR00430
      W2=XX(3)                                                          FIR00440
      W3=XX(4)                                                          FIR00450
C SHIFT REGISTERS                                                       FIR00460
      X1=0.0                                                            FIR00470
      X2=0.0                                                            FIR00480
      X3=0.0                                                            FIR00490
C SIMULATE DESIRED OUTPUT SIGNAL                                        FIR00500
      DO 15 I=1,105                                                     FIR00510
15        DESIRE(I)=-1.0                                               FIR00520
      DO 16 I=1,11                                                      FIR00530
16        DESIRE(I+44)=1.0                                             FIR00540
C                                                                      FIR00550
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      KE=0                                              FIR08260
      RETURN                                            FIR08270
      END                                               FIR08280
```

```
      1 '   NEW MIN IS ',E15.7)                                          FIR07710
   56 FORMAT ('OMIN OBJECTIVE FUNCTION IS ',E15.7)                       FIR07720
      END                                                                FIR07730
      SUBROUTINE FBV (K,FUN,M)                                           FIR07740
      DIMENSION FUN(50)                                                  FIR07750
      M = 1                                                              FIR07760
C                                                                        FIR07770
      DO 1 I=2,K                                                         FIR07780
      IF (FUN(M).LE.FUN(I)) GO TO 1                                      FIR07790
      M = I                                                              FIR07800
    1 CONTINUE                                                           FIR07810
C                                                                        FIR07820
      RETURN                                                             FIR07830
      END                                                                FIR07840
      SUBROUTINE BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FN,C,IK)                FIR07850
      DIMENSION V(50,50), FN(50), C(25)                                  FIR07860
      WRITE (6,4) NT,NPT,NFE,NCE                                         FIR07870
C  .                                                                     FIR07880
      DO 1 I=1,K                                                         FIR07890
      WRITE (6,5) FN(I),(V(J,I),J=1,NV)                                  FIR07900
      IF (NVT.LE.NV) GO TO 1                                             FIR07910
      NVP = NV+1                                                         FIR07920
      WRITE (6,6) (V(J,I),J=NVP,NVT)                                     FIR07930
    1 CONTINUE                                                           FIR07940
C                                                                        FIR07950
      IF (IK.NE.0) GO TO 2                                               FIR07960
C                                                                        FIR07970
      WRITE (6,7) (C(I),I=1,NV)                                          FIR07980
      RETURN                                                             FIR07990
    2 IF (IK.GE.0) GO TO 3                                               FIR08000
      WRITE (6,8) (C(I),I=1,NV)                                          FIR08010
      RETURN                                                             FIR08020
    3 WRITE (6,9) IK,(C(I),I=1,NV)                                       FIR08030
      RETURN                                                             FIR08040
C        .                                                               FIR08050
    4 FORMAT ('ONO. TOTAL TRIALS = ',I5,4X,'NO. FEASIBLE TRIALS = ',     FIR08060
     115,4X,'NO. FUNCTION EVALUATIONS = ',I5,4X,'NO. CONSTRAINT EVALUATIFIR08070
     2ONS = ',I5/'0      FUNCTION VALUE',6X,'INDEPENDENT VARIABLES/DEPENDFIR08080
     3ENT OR IMPLICIT CONSTRAINTS')                                      FIR08090
    5 FORMAT (1H ,E18.7,2X,7E14.7/(21X,7E14.7))                          FIR08100
    6 FORMAT (21X,7E14.7)                                                FIR08110
    7 FORMAT (10HOCENTROID 11X,7E14.7/(21X,7E14.7))                      FIR08120
    8 FORMAT ('0  BEST VERTEX',7X,7E14.7/(21X,7E14.7))                   FIR08130
    9 FORMAT ('OCENTROID LESS VX',I2,2X,7E14.7/(21X,7E14.7))             FIR08140
      END                                                                FIR08150
      FUNCTION FE(X)                                                     FIR08160
      DIMENSION X(4)                                                     FIR08170
      REAL J                                                             FIR08180
      COMMON J                                                           FIR08190
      CALL FIR(X)                                                        FIR08200
      FE=J                                                               FIR08210
      RETURN                                                             FIR08220
      END                                                                FIR08230
      FUNCTION KE(X)·                                                    FIR08240
      DIMENSION X(4)                                                     FIR08250
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C   IF NOT, GO TO NEW TRIAL.                                          FIR07160
   40 IF (NT.GE.NTA) GO TO 41                                         FIR07170
C                                                                     FIR07180
C   NEXT-TO-WORST VERTEX NOW BECOMES WORST.                           FIR07190
      J = JN                                                          FIR07200
      GO TO 17                                                        FIR07210
   41 IER = 3                                                         FIR07220
      IF (NPR.GT.0) WRITE (6,54)                                      FIR07230
C                                                                     FIR07240
C   COLLECTOR POINT FOR ALL ENDINGS.                                  FIR07250
C     1)  CANNOT DEVELOP FEASIBLE VERTEX.            IER = 1          FIR07260
C     2)  CANNOT DEVELOP A NO-LONGER-WORST VERTEX.   IER = 2          FIR07270
C     3)  FUNCTION VALUE UNCHANGED FOR K TRIALS.     IER = 0          FIR07280
C     4)  LIMIT ON TRIALS REACHED.                   IER = 3          FIR07290
C     5)  CANNOT FIND FEASIBLE VERTEX AT START.      IER = -1         FIR07300
   42 CONTINUE                                                        FIR07310
C                                                                     FIR07320
C · FIND BEST VERTEX.                                                 FIR07330
      CALL FBV (K,FUN,M)                                              FIR07340
      IF (IER.GE.3) GO TO 44                                          FIR07350
C                                                                     FIR07360
C   RESTART IF THIS SOLUTION IS SIGNIFICANTLY BETTER THAN THE PREVIOUS, FIR07370
C   OR IF THIS IS THE FIRST TRY.                                      FIR07380
      IF (NPR.LE.0) GO TO 43                                          FIR07390
      WRITE (6,55) (M,YMN,FUN(M))                                     FIR07400
   43 IF (FUN(M).GE.YMN) GO TO 47                                     FIR07410
      IF (ABS(FUN(M)-YMN).LE.AMAX1(EP,EP*YMN)) GO TO 47               FIR07420
C                                                                     FIR07430
C   GIVE IT ANOTHER TRY UNLESS LIMIT ON TRIALS REACHED.               FIR07440
   44 YMN = FUN(M)                                                    FIR07450
      FUN(1) = FUN(M)                                                 FIR07460
C                                                                     FIR07470
      DO 45 I=1,NV                                                    FIR07480
      CEN(I) = V(I,M)                                                 FIR07490
      SUM(I) = V(I,M)                                                 FIR07500
   45 V(I,1) = V(I,M)                                                 FIR07510
C                                                                     FIR07520
      DO 46 I=1,NVT                                                   FIR07530
   46 XS(I) = V(I,M)                                                  FIR07540
C                                                                     FIR07550
      IF (IER.LT.3) GO TO 6                                           FIR07560
   47 IF (NPR.LE.0) GO TO 48                                          FIR07570
      CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,V(1,M),-1)             FIR07580
      WRITE (6,56) FUN(M)                                             FIR07590
   48 RETURN                                                          FIR07600
C                                                                     FIR07610
   49 FORMAT (50HOINDEX AND DIRECTION OF OUTLYING VARIABLE AT STARTI5) FIR07620
   50 FORMAT (50HOIMPLICIT CONSTRAINT VIOLATED AT START. DEAD END. )  FIR07630
   51 FORMAT ('OCANNOT FIND FEASIBLE',I4,'TH VERTEX OR CENTROID AT STARTFIR07640
     1.')                                                             FIR07650
   52 FORMAT (10HOAT TRIAL I4,54H CANNOT FIND FEASIBLE VERTEX WHICH IS NFIR07660
     10 LONGER WORST,I4,15X,'RESTART FROM BEST VERTEX.')              FIR07670
   53 FORMAT (40HOFUNCTION HAS BEEN ALMOST UNCHANGED FOR I5,7H TRIALS) FIR07680
   54 FORMAT (27HOLIMIT ON TRIALS EXCEEDED. )                         FIR07690
   55 FORMAT ('OBEST VERTEX IS NO.',I3,'  OLD MIN WAS ',E15.7,        FIR07700
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      IF (IP.EQ.1) VT = AINT(VT+.5)                              FIR06610
   29 V(I,J) = AMAX1(AMIN1(VT,BU(I)),BL(I))                      FIR06620
C                                                                FIR06630
      GO TO 32                                                   FIR06640
C                                                                FIR06650
   30 DO 31 I=1,NV                                               FIR06660
      VT = .5*(CEN(I)+V(I,J))                                    FIR06670
      IF (IP.EQ.1) VT = AINT(VT+.5)                              FIR06680
      V(I,J) = VT                                                FIR06690
   31 CONTINUE                                                   FIR06700
C                                                                FIR06710
   32 IF (LIMT.LT.NLIM) GO TO 33                                 FIR06720
C                                                                FIR06730
C  CANNOT MAKE THE 'J'TH VERTEX NO LONGER WORST BY DISPLACING TOWARD  FIR06740
C  THE CENTROID OR BY OVER-REFLECTING THRU THE BEST VERTEX.     FIR06750
      IER = 2                                                    FIR06760
      IF (NPR .LE. 0)  GO TO 42                                  FIR06770
      WRITE (6,52)  NT, J                                        FIR06780
      CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,CEN,J)            FIR06790
      GO TO 42                                                   FIR06800
   33 NT = NT+1                                                  FIR06810
      GO TO 20                                                   FIR06820
C                                                                FIR06830
C  SUCCESS:  WE HAVE A REPLACEMENT FOR VERTEX J.                FIR06840
   34 FUN(J) = FUNTRY                                            FIR06850
      FUNOLD = FUNTRY                                            FIR06860
      NPT = NPT+1                                                FIR06870
C                                                                FIR06880
C  EVERY 100'TH PERMISSIBLE TRIAL, RECOMPUTE CENTROID SUMMATION TO  FIR06890
C  AVOID CREEPING ERROR.                                        FIR06900
      IF (MOD(NPT,100).NE.0) GO TO 37                            FIR06910
C                                                                FIR06920
      DO 36 I=1,NV                                               FIR06930
      SUM(I) = 0.                                                FIR06940
C                                                                FIR06950
      DO 35 N=1,K                                                FIR06960
   35 SUM(I) = SUM(I)+V(I,N)                                     FIR06970
C                                                                FIR06980
      CEN(I) = SUM(I)/FK                                         FIR06990
   36 CONTINUE                                                   FIR07000
C                                                                FIR07010
      LC = 0                                                     FIR07020
      GO TO 39                                                   FIR07030
C                                                                FIR07040
   37 DO 38 I=1,NV                                               FIR07050
   38 SUM(I) = SUM(I)+V(I,J)                                     FIR07060
C                                                                FIR07070
      LC = J                                                     FIR07080
C                                                                FIR07090
   39 IF (NPR.LE.0) GO TO 40                                     FIR07100
      IF (MOD(NPT,NPR).NE.0) GO TO 40                            FIR07110
C                                                                FIR07120
      CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,CEN,LC)           FIR07130
C                                                                FIR07140
C  HAS THE MAX. NUMBER OF TRIALS BEEN REACHED WITHOUT CONVERGENCE?  FIR07150
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      GO TO 24                                                        FIR06060
C                                                                     FIR06070
C   CONSTRAINT VIOLATION:  MOVE NEW POINT TOWARD CENTROID.            FIR06080
C                                                                     FIR06090
   22 DO 23 I=1,NV                                                    FIR06100
      VT = .5*(CEN(I)+V(I,J))                                         FIR06110
      IF (IP.EQ.1) VT = AINT(VT+.5)                                   FIR06120
      V(I,J) = VT                                                     FIR06130
   23 CONTINUE                                                        FIR06140
C                                                                     FIR06150
   24 NT = NT+1                                                       FIR06160
   25 CONTINUE                                                        FIR06170
C                                                                     FIR06180
      IER = 1                                                         FIR06190
C                                                                     FIR06200
C   CANNOT GET FEASIBLE VERTEX BY MOVING TOWARD CENTROID,             FIR06210
C   OR BY OVER-REFLECTING THRU THE BEST VERTEX.                       FIR06220
      IF (NPR.LE.0) GO TO 42                                          FIR06230
      WRITE (6,52) NT,J                                               FIR06240
      CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,CEN,J)                 FIR06250
      GO TO 42                                                        FIR06260
C                                                                     FIR06270
C   FEASIBLE VERTEX FOUND, EVALUATE THE OBJECTIVE FUNCTION.           FIR06280
   26 NFE = NFE+1                                                     FIR06290
      FUNTRY = FE(V(1,J))                                             FIR06300
C                                                                     FIR06310
C   TEST TO SEE IF FUNCTION VALUE HAS NOT CHANGED.                    FIR06320
      AFO = ABS(FUNTRY-FUNOLD)                                        FIR06330
      AMX = AMAX1(ABS(EP*FUNOLD),EP)                                  FIR06340
C                                                                     FIR06350
C   ACTIVATE THE FOLLOWING TWO STATEMENTS FOR DIAGNOSTIC PURPOSES ONLY. FIR06360
C     WRITE (6,99) J,AFO,AMX,FUNTRY,FUNOLD,FUN(J),FUN(JN),NTFS,N      FIR06370
C  99 FORMAT (1X,I3,6E15.7,2I5)                                       FIR06380
      IF (AFO.GT.AMX) GO TO 27                                        FIR06390
      NTFS = NTFS+1                                                   FIR06400
      IF (NTFS.LT.NCT) GO TO 28                                       FIR06410
      IER = 0                                                         FIR06420
      IF (NPR.LE.0) GO TO 42                                          FIR06430
      WRITE (6,53) K                                                  FIR06440
      CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,CEN,0)                 FIR06450
      GO TO 42                                                        FIR06460
   27 NTFS = 0                                                        FIR06470
C                                                                     FIR06480
C   IS THE NEW VERTEX NO LONGER WORST?                                FIR06490
   28 IF (FUNTRY.LT.FUN(JN)) GO TO 34                                 FIR06500
C                                                                     FIR06510
C   TRIAL VERTEX IS STILL WORST; ADJUST TOWARD CENTROID.              FIR06520
C   EVERY 'KV'TH TIME, OVER-REFLECT THE OFFENDING VERTEX THROUGH THE  FIR06530
C   BEST VERTEX.                                                      FIR06540
      LIMT = LIMT+1                                                   FIR06550
      IF (MOD(LIMT,KV).NE.0) GO TO 30                                 FIR06560
      CALL FBV (K,FUN,M)                                              FIR06570
C                                                                     FIR06580
      DO 29 I=1,NV                                                    FIR06590
      VT = BETA*V(I,M)-ALPHA*V(I,J)                                   FIR06600
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C                                                               FIR05510
C   FIND THE WORST VERTEX, THE 'J'TH.                           FIR05520
      J = 1                                                     FIR05530
C                                                               FIR05540
      DO 16 I=2,K                                               FIR05550
      IF (FUN(J).GE.FUN(I)) GO TO 16                            FIR05560
      J = I                                                     FIR05570
   16 CONTINUE                                                  FIR05580
C                                                               FIR05590
C   BASIC LOOP.  ELIMINATE EACH WORST VERTEX IN TURN.  IT MUST BECOME  FIR05600
C   NO LONGER WORST, NOT MERELY IMPROVED.  FIND NEXT-TO-WORST VERTEX,  FIR05610
C   THE 'JN'TH ONE.                                             FIR05620
   17 JN = 1                                                    FIR05630
      IF (J.EQ.1) JN = 2                                        FIR05640
C                                                               FIR05650
      DO 18 I=1,K                                               FIR05660
      IF (I.EQ.J) GO TO 18                                      FIR05670
      IF (FUN(JN).GE.FUN(I)) GO TO 18                           FIR05680
      JN = I                                                    FIR05690
   18 CONTINUE                                                  FIR05700
C                                                               FIR05710
C   LIMT = NUMBER OF MOVES DURING THIS TRIAL TOWARD THE CENTROID  FIR05720
C    DUE TO FUNCTION VALUE.                                     FIR05730
      LIMT = 1                                                  FIR05740
C                                                               FIR05750
C   COMPUTE CENTROID AND OVER REFLECT WORST VERTEX.             FIR05760
C                                                               FIR05770
      DO 19 I=1,NV                                              FIR05780
      VT = V(I,J)                                               FIR05790
      SUM(I) = SUM(I)-VT                                        FIR05800
      CEN(I) = SUM(I)/FKM                                       FIR05810
      VT = BETA*CEN(I)-ALPHA*VT                                 FIR05820
      IF (IP.EQ.1) VT = AINT(VT+.5)                             FIR05830
C                                                               FIR05840
C   INSURE THE EXPLICIT CONSTRAINTS ARE OBSERVED.              FIR05850
   19 V(I,J) = AMAX1(AMIN1(VT,BU(I)),BL(I))                     FIR05860
C                                                               FIR05870
      NT = NT+1                                                 FIR05880
C                                                               FIR05890
C   CHECK FOR IMPLICIT CONSTRAINT VIOLATION.                    FIR05900
C                                                               FIR05910
   20 DO 25 N=1,NLIM                                            FIR05920
      NCE = NCE+1                                               FIR05930
      IF (KE(V(1,J)).EQ.0) GO TO 26                             FIR05940
C                                                               FIR05950
C   EVERY 'KV'TH TIME, OVER-REFLECT THE OFFENDING VERTEX THROUGH THE  FIR05960
C   BEST VERTEX.                                                FIR05970
      IF (MOD(N,KV).NE.0) GO TO 22                              FIR05980
      CALL FBV (K,FUN,M)                                        FIR05990
C                                                               FIR06000
      DO 21 I=1,NV                                              FIR06010
      VT = BETA*V(I,M)-ALPHA*V(I,J)                             FIR06020
      IF (IP.EQ.1) VT = AINT(VT+.5)                             FIR06030
   21 V(I,J) = AMAX1(AMIN1(VT,BU(I)),BL(I))                     FIR06040
C                                                               FIR06050
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      FUNOLD = FUN(1)                                        FIR04960
C                                                            FIR04970
      DO 15 I=2,K                                            FIR04980
      FI = FI+1.                                             FIR04990
      LIMT = 0                                               FIR05000
    7 LIMT = LIMT+1                                          FIR05010
C                                                            FIR05020
C   END CALCULATION IF FEASIBLE CENTROID CANNOT BE FOUND.    FIR05030
      IF (LIMT.GE.NLIM) GO TO 11                             FIR05040
C                                                            FIR05050
      DO 8 J=1,NV                                            FIR05060
C                                                            FIR05070
C   RANDOM NUMBER GENERATOR   (RANDU)                        FIR05080
      IQR = IQR*65539                                        FIR05090
      IF (IQR.LT.0) IQR = IQR+2147483647+1                   FIR05100
      RQX = IQR                                              FIR05110
      RQX = RQX*.4656613E-9                                  FIR05120
      V(J,I) = BL(J)+RQX*(BU(J)-BL(J))                       FIR05130
      IF (IP.EQ.1) V(J,I)=AINT(V(J,I)+.5)                    FIR05140
    8 CONTINUE                                               FIR05150
C                                                            FIR05160
      DO 10 L=1,NLIM                                         FIR05170
      NCE = NCE+1                                            FIR05180
      IF (KE(V(1,I)).EQ.0) GO TO 13                          FIR05190
C                                                            FIR05200
      DO 9 J=1,NV                                            FIR05210
      VT = .5*(V(J,I)+CEN(J))                                FIR05220
      IF (IP.EQ.1) VT = AINT(VT+.5)                          FIR05230
      V(J,I) = VT                                            FIR05240
    9 CONTINUE                                               FIR05250
C                                                            FIR05260
   10 CONTINUE                                               FIR05270
C                                                            FIR05280
   11 IF (NPR.LE.0) GO TO 12                                 FIR05290
      WRITE (6,51) I                                         FIR05300
      CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,I,FUN,CEN,I)        FIR05310
   12 IER = -1                                               FIR05320
      GO TO 48                                               FIR05330
C                                                            FIR05340
   13 DO 14 J=1,NV                                           FIR05350
      SUM(J) = SUM(J)+V(J,I)                                 FIR05360
   14 CEN(J) = SUM(J)/FI                                     FIR05370
C                                                            FIR05380
C   TRY TO ASSURE FEASIBLE CENTROID FOR STARTING.            FIR05390
      NCE = NCE+1                                            FIR05400
      IF (KE(CEN).EQ.0) GO TO 60                             FIR05410
      SUM(J) = SUM(J) -V(J,I)                                FIR05420
      GO TO 7                                                FIR05430
   60 NFE = NFE+1                                            FIR05440
      FUN(I) = FE(V(1,I))                                    FIR05450
   15 CONTINUE                                               FIR05460
C                                                            FIR05470
C   END OF LOOP SETTING OF INITIAL COMPLEX.                  FIR05480
      IF (NPR.LE.0) GO TO 17                                 FIR05490
      CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,CEN,0)        FIR05500
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      NPT = 0                                                    FIRO4410
C           CURRENT NO. OF PERMISSIBLE TRIALS                    FIRO4420
      NTFS = 0                                                   FIRO4430
C           CURRENT NO. OF TIMES F HAS BEEN ALMOST UNCHANGED     FIRO4440
C                                                                FIRO4450
C              CHECK FEASIBILITY OF START POINT                  FIRO4460
C                                                                FIRO4470
      DO 4 I=1,NV                                                FIRO4480
      VT = XS(I)                                                 FIRO4490
      IF (BL(I).LE.VT) GO TO 1                                   FIRO4500
      II = -I                                                    FIRO4510
      VT = BL(I)                                                 FIRO4520
      GO TO 2                                                    FIRO4530
    1 IF (BU(I).GE.VT) GO TO 3                                   FIRO4540
      II = I                                                     FIRO4550
      VT = BU(I)                                                 FIRO4560
    2 IF (NPR.GT.0) WRITE (6,49) II                             FIRO4570
    3 V(I,1) = VT                                                FIRO4580
      CEN(I) = VT                                                FIRO4590
      IF (IP.EQ.1) GO TO 4                                       FIRO4600
      BL(I) = BL(I)+AMAX1(EP,EP*ABS(BL(I)))                      FIRO4610
      BU(I) = BU(I)-AMAX1(EP,EP*ABS(BU(I)))                      FIRO4620
    4 SUM(I) = VT                                                FIRO4630
C                                                                FIRO4640
C                                                                FIRO4650
      NCE = 1                                                    FIRO4660
C           NUMBER OF CONSTRAINT EVALUATIONS                     FIRO4670
      I = 1                                                      FIRO4680
      IF (KE(V(1,1)).EQ.0) GO TO 5                               FIRO4690
      IF (NPR.LE.0) GO TO 12                                     FIRO4700
      WRITE (6,50)                                               FIRO4710
      GO TO 12                                                   FIRO4720
    5 NFE = 1                                                    FIRO4730
C                                                                FIRO4740
C  NUMBER OF VERTICES (K) = 2 TIMES NO. OF VARIABLES.           FIRO4750
      K = 2*NV                                                   FIRO4760
C                                                                FIRO4770
C  NUMBER OF DISPLACEMENTS ALLOWED.                             FIRO4780
      NLIM = 5*NV+10                                             FIRO4790
C                                                                FIRO4800
C  NUMBER OF CONSECUTIVE TRIALS WITH UNCHANGED FE TO TERMINATE. FIRO4810
      NCT = NLIM+NV                                              FIRO4820
      ALPHA = 1.3                                                FIRO4830
      FK = K                                                     FIRO4840
      FKM = FK-1.                                                FIRO4850
      BETA = ALPHA+1.                                            FIRO4860
C                                                                FIRO4870
C  INSURE SEED OF RANDOM NUMBER GENERATOR IS ODD.               FIRO4880
      IQR = R*1.E7                                               FIRO4890
      IF (MOD(IQR,2).EQ.0) IQR=IQR+101                           FIRO4900
C                                                                FIRO4910
C                   SET UP INITIAL VERTICES                      FIRO4920
      FUN(1) = FE(V(1,1))                                        FIRO4930
      YMN = FUN(1)                                               FIRO4940
    6 FI = 1.                                                    FIRO4950
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C           SUBROUTINE 'BOUT' AND FUNCTION 'FBV' ARE INTEGRAL PARTS OF     FIR03860
C           THE BOXPLX PACKAGE.                                           FIR03870
C                                                                         FIR03880
C           TWO FUNCTIONS MUST BE SUPPLIED BY THE USE4   THE FIRST, KE(X),FIR03890
C           IS USED TO EVALUATE THE IMPLICIT CONSTRAIN1.   SET KE=0 AT THEFIR03900
C           BEGINING OF THE FUNCTION, THEN EVALUATE THE IMPLICIT CON-     FIR03910
C           STRAINTS.   IN THE EXAMPLE ABOVE, THE FIRST CONSTRAINT, X(3), FIR03920
C           MUST BE WITHIN THE RANGE (0. .LE. X(3) .LE. 6.).   THE SECOND FIR03930
C           CONSTRAINT X(4), MUST BE .GE. 0. .   IF EITHER CONSTRAINT IS  FIR03940
C           NOT WITHIN THESE BOUNDS, CONTROL IS TRANSFERRED TO STATEMENT 1,FIR03950
C           AND KE IS SET TO "1" AND CONTROL IS RETURNED TO BOXPLX.       FIR03960
C                                                                         FIR03970
C           THE SECOND FUNCTION THE USER MUST PROVIDE EVALUATES THE OB-   FIR03980
C           JECTIVE FUNCTION.   IT IS CALLED FE(X) AS SHOWN IN THE EXAM-  FIR03990
C           PLE ABOVE, AND FE MUST BE SET TO THE VALUE OF THE OBJECTIVE   FIR04000
C           FUNCTION CORRESPONDING TO CURRENT VALUES OF THE NV INDEPENDENT FIR04010
C           VARIABLES IN ARRAY 'X'.                                       FIR04020
C                                                                         FIR04030
C     REFERENCES                                                          FIR04040
C                                                                         FIR04050
C        BOX, M. J., "A NEW METHOD OF CONSTRAINED OPTIMIZATION AND A      FIR04060
C        COMPARISON WITH OTHER METHODS", COMPUTER JOURNAL, 8 APR. '65,    FIR04070
C        PP. 45-52.                                                       FIR04080
C                                                                         FIR04090
C        BEVERIDGE G., AND SCHECHTER R., "OPTIMIZATION: THEORY AND        FIR04100
C        PRACTICE", MCGRAW-HILL, 1970.                                    FIR04110
C                                                                         FIR04120
C     PROGRAMMER                                                          FIR04130
C                                                                         FIR04140
C        R.R. HILLEARY 1/1966.                                           FIR04150
C        REVISED FOR SYSTEM 360 4/1967                                   FIR04160
C        CORRECTED  1/1969                                               FIR04170
C        REVISED/EXTENDED BY L.NOLAN/R.HILLEARY  2/1975                  FIR04180
C        CORRECTED  8/1976                                               FIR04190
C                                                                         FIR04200
C                                                                         FIR04210
C     ......................................................FIR04220
C                                                                         FIR04230
C                                                                         FIR04240
      SUBROUTINE BOXPLX (NV,NAV,NPR,NTZ,RZ,XS,IP,BU,BL,YMN,IER)          FIR04250
C                                                                         FIR04260
      DIMENSION V(50,50), FUN(50), SUM(25), CEN(25), XS(NV), BU(NV), BL(FIR04270
     1NV)                                                                 FIR04280
C                                                                         FIR04290
      KV = 5                                                              FIR04300
      EP = 1.E-6                                                          FIR04310
      NTA = 2000                                                          FIR04320
      IF (NTZ.GT.0) NTA = NTZ                                             FIR04330
      R = RZ                                                              FIR04340
      IF (R.LE.0..OR.R.GE.1.) R=1./3.                                     FIR04350
      NVT = NV+NAV                                                        FIR04360
C                                                                         FIR04370
C           TOTAL VARS, EXPLICIT PLUS IMPLICIT                           FIR04380
      NT = 0                                                              FIR04390
C           CURRENT TRIAL NO.                                           FIR04400
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C          THE REPLACED VERTEX AND CENTROID OF ALL OTHER VERTICES.)      FIR03310
C                                                                        FIR03320
C          WHEN AN OVER-REFLECTION IS NOT FEASIBLE OR REMAINS WORST, IT  FIR03330
C          IS CONSIDERED NOT-PERMISSIBLE AND IS DISPLACED HALFWAY TOWARD FIR03340
C          THE CENTROID.  AFTER FOUR SUCH ATTEMPTS ARE MADE UNSUCCESSFULLYFIR03350
C          EVERY FIFTH ATTEMPT IS MADE BY REFLECTING THE OFFENDING VERTEX FIR03360
C          THROUGH THE PRESENT BEST VERTEX, INSTEAD OF THROUGH THE CEN-  FIR03370
C          TROID.  IF 5*N+10 DISPLACEMENTS AND OVER-REFLECTIONS OCCUR    FIR03380
C          WITHOUT A SUCCESSFUL (PERMISSIBLE) RESULT, THE CURRENT BEST   FIR03390
C          VERTEX IS TAKEN AS AN INITIAL FEASIBLE POINT FOR A RESTART    FIR03400
C          RUN OF THE COMPLETE PROCESS.  RESTARTING IS ALSO UNDERTAKEN   FIR03410
C          WHEN 6*NV+10 CONSECUTIVE TRIALS HAVE BEEN MADE WITH NO SIGNIF- FIR03420
C          ICANT CHANGE IN THE VALUE OF THE OBJECTIVE FUNCTION.  IN ALL  FIR03430
C          CASES, RESTARTING IS INHIBITED IF THE LAST RESTART DID NOT    FIR03440
C          PRODUCE A SIGNIFICANT IMPROVEMENT IN THE MINIMUM ATTAINED.    FIR03450
C                                                                        FIR03460
C          IT IS RECOMMENDED THAT THE USER READ THE REFERENCE FOR        FIR03470
C   .      FURTHER USEFUL INFORMATION.  IT SHOULD BE NOTED THAT THE      FIR03480
C          ALGORITHM DEFINED THERE HAS BEEN ALTERED TO FIND THE          FIR03490
C          CONSTRAINED MINIMUM, RATHER THAN THE MAXIMUM.                 FIR03500
C                                                                        FIR03510
C                                                                        FIR03520
C                                                                        FIR03530
C     REMARKS                                                            FIR03540
C                                                                        FIR03550
C          THE INTEGER PROGRAMMING OPTION WAS ADDED TO THIS PROGRAM      FIR03560
C          AS SUGGESTED IN REFERENCE (2).  A MIXED INTEGER/CONTINUOUS    FIR03570
C          VARIABLE VERSION OF BOXPLX WOULD BE EASY TO CREATE BY DE-     FIR03580
C          CLARING "IP" TO BE AN ARRAY OF NV CONTROL VARIABLES WHERE IP  FIR03590
C          (I)=1 WOULD INDICATE THAT THE I-TH VARIABLE IS TO BE CONFINED FIR03600
C          TO INTEGER VALUES.  EACH STATEMENT OF THE FORM 'IF (IP .EQ.   FIR03610
C          1)' ETC. WOULD THEN NEED TO BE ALTERED TO 'IF (IP(I) .EQ. 1)' FIR03620
C          ETC., WHERE THE SUBSCRIPT IS APPROPRIATELY CHOSEN.  NORMALLY, FIR03630
C          XU AND XL VALUES ARE ALTERED TO BE AN EPSILON 'WITHIN' ACTUAL FIR03640
C          VALUES DECLARED BY THE USER.  THIS ADJUSTMENT IS NOT MADE     FIR03650
C          WHEN IP=1.                                                    FIR03660
C                                                                        FIR03670
C          NOTE:  NO NON-LINEAR PROGRAMMING ALGORITHM CAN GUARANTEE THAT FIR03680
C          THE ANSWER FOUND IS THE GLOBAL MINIMUM, RATHER THAN JUST A    FIR03690
C          LOCAL MINIMUM.  HOWEVER, ACCORDING TO REF.2, THE COMPLEX      FIR03700
C          METHOD HAS AN ADVANTAGE IN THAT IT TENDS TO FIND THE GLOBAL   FIR03710
C          MINIMUM MORE FREQUENTLY THAN MANY OTHER NON-LINEAR PROGRAM-   FIR03720
C          MING ALGORITHMS.                                              FIR03730
C                                                                        FIR03740
C          IT SHOULD BE NOTED THAT THE AUXILIARY VARIABLE FEATURE CAN    FIR03750
C          ALSO BE USED TO DEAL WITH PROBLEMS CONTAINING EQUALITY CON-   FIR03760
C          STRAINTS.  ANY EQUALITY CONSTRAINT IMPLIES THAT A GIVEN VAR-  FIR03770
C          IABLE IS NOT TRULY INDEPENDENT.  THEREFORE, IN GENERAL, ONE   FIR03780
C          VARIABLE INVOLVED IN AN EQUALITY CONSTRAINT CAN BE RENUMBERED FIR03790
C          FROM THE SET OF NV INDEPENDENT VARIABLES AND ADDED TO THE SET FIR03800
C          OF NAV AUXILIARY VARIABLES.  THIS USUALLY INVOLVES RENUMBERING FIR03810
C          THE INDEPENDENT VARIABLES OF THE GIVEN PROBLEM.              FIR03820
C                                                                        FIR03830
C     SUBROUTINES AND FUNCTIONS REQUIRED                                 FIR03840
C                                                                        FIR03850
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CC                                                                    FIR02760
C      FUNCTION KE(X)                                                 FIR02770
CC  EVALUATE CONSTRAINTS.  SET KE=0 IF NO IMPLICIT CONSTRAINT IS      FIR02780
CC  VIOLATED, OR SET KE=1 IF ANY IMPLICIT CONSTRAINT IS VIOLATED.     FIR02790
C      DIMENSION X(4)                                                 FIR02800
C      X1 = X(1)                                                      FIR02810
C      X2 = X(2)                                                      FIR02820
C      KE = 0                                                         FIR02830
C      X(3) = X1 + 1.732051*X2                                        FIR02840
C      IF (X(3) .LT. 0. .OR. X(3) .GT. 6.) GO TO 1                    FIR02850
C      X(4) = X1/1.732051 -X2                                         FIR02860
C      IF (X(4) .GE. 0.)  RETURN                                      FIR02870
CC                                                                    FIR02880
C    1 KE = 1                                                         FIR02890
C      RETURN                                                         FIR02900
C      END                                                            FIR02910
CC                                                                    FIR02920
CC·                                                                   FIR02930
C      FUNCTION  FE(X)                                                FIR02940
C      DIMENSION X(4)                                                 FIR02950
CC                                                                    FIR02960
CC  THIS IS THE OBJECTIVE FUNCTION.                                   FIR02970
C      FE= -(X(2)**3 *(9.-(X(1)-3.)**2)/(46.76538))                   FIR02980
C      RETURN                                                         FIR02990
C      END                                                            FIR03000
C                                                                     FIR03010
C      METHOD                                                         FIR03020
C                                                                     FIR03030
C          THE COMPLEX METHOD IS AN EXTENSION AND ADAPTION OF THE SIM- FIR03040
C          PLEX METHOD OF LINEAR PROGRAMMING.  STARTING WITH ANY ONE  FIR03050
C.         FEASIBLE POINT IN N-DIMENSION SPACE A "COMPLEX" OF 2*N     FIR03060
C          VERTICES IS CONSTRUCTED BY SELECTING RANDOM POINTS WITHIN THE FIR03070
C          FEASIBLE REGION.  FOR THIS PURPOSE N COORDINATES ARE FIRST FIR03080
C          RANDOMLY CHOSEN WITHIN THE SPACE BOUNDED BY EXPLICIT CON-  FIR03090
C          STRAINTS.  THIS DEFINES A TRIAL INITIAL VERTEX.  IT IS THEN FIR03100
C          CHECKED FOR POSSIBLE VIOLATION OF IMPLICIT CONSTRAINTS.  IF FIR03110
C          ONE OR MORE ARE VIOLATED, THE TRIAL INITIAL VERTEX IS DISPLACEDFIR03120
C          HALF OF ITS DISTANCE FROM THE CENTROID OF PREVIOUSLY SELECTED FIR03130
C          INITIAL VERTICES.  IF NECESSARY THIS DISPLACEMENT PROCESS IS FIR03140
C          REPEATED UNTIL THE VERTEX HAS BECOME FEASIBLE.  IF THIS FAILS FIR03150
C          TO HAPPEN AFTER 5*N+10 DISPLACEMENTS, THE SOLUTION IS ABAND- FIR03160
C          ONED.  AFTER EACH VERTEX IS ADDED TO THE COMPLEX, THE CURRENT FIR03170
C          CENTROID IS CHECKED FOR FEASIBILITY.  IF IT IS INFEASIBLE, FIR03180
C          THE LAST TRIAL VERTEX IS ABANDONED AND AN EFFORT TO GENERATE FIR03190
C          AN ALTERNATIVE TRIAL VERTEX IS MADE.  IF 5*N+10 VERTICES ARE FIR03200
C          ABANDONED CONSECUTIVELY, THE SOLUTION IS TERMINATED.       FIR03210
C                                                                     FIR03220
C          IF AN INITIAL COMPLEX IS ESTABLISHED, THE BASIC COMPUTATION FIR03230
C          LOOP IS INITIATED.  THESE INSTRUCTIONS FIND THE CURRENT WORST FIR03240
C          VERTEX, THAT IS, THE VERTEX WITH THE LARGEST CORRESPONDING FIR03250
C          VALUE FOR THE OBJECTIVE FUNCTION, AND REPLACE THAT VERTEX BY FIR03260
C          ITS OVER-REFLECTION THROUGH THE CENTROID OF ALL OTHER VERTICES.FIR03270
C          (IF THE VERTEX TO BE REPLACED IS CONSIDERED AS A VECTOR IN FIR03280
C          N-SPACE, ITS OVER-REFLECTION IS OPPOSITE IN DIRECTION, IN- FIR03290
C          CREASED IN LENGTH BY THE FACTOR 1.3, AND COLLINEAR WITH    FIR03300
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C                       VALUES IF NONE ARE GIVEN, NOT VALUES WHICH ARE MAGNITUDES   FIR02210
C                       ABOVE OR BELOW THE EXPECTED SOLUTION.  INPUT VALUES ARE      FIR02220
C                       SLIGHTLY ALTERED BY BOXPLX.                                  FIR02230
C                                                                                    FIR02240
C            YMN   THIS OUTPUT IS THE VALUE (REAL*4) OF THE OBJECTIVE FUNC-          FIR02250
C                  TION, CORRESPONDING TO THE SOLUTION POINT OUTPUT IN XS.           FIR02260
C                                                                                    FIR02270
C            IER   INTEGER ERROR RETURN.  TO BE INTERROGATED UPON RETURN             FIR02280
C                  . FROM BOXPLX.  IER WILL BE ONE OF THE FOLLOWING:                 FIR02290
C                                                                                    FIR02300
C                  =-1   CANNOT FIND FEASIBLE VERTEX OR FEASIBLE CENTROID            FIR02310
C                        AT THE START OR A RESTART (SEE 'METHOD' BELOW).             FIR02320
C                  =0    FUNCTION VALUE UNCHANGED FOR 'N' TRIALS.  (WHERE            FIR02330
C                        N=6*NV+10)  THIS IS THE NORMAL RETURN PARAMETER.            FIR02340
C                  =1    CANNOT DEVELOP FEASIBLE VERTEX.                             FIR02350
C                  =2    CANNOT DEVELOP A NO-LONGER-WORST VERTEX.                    FIR02360
C                  =3    LIMIT ON TRIALS REACHED.  (NTA EXCEEDED)                    FIR02370
C   .              NOTE:  VALID RESULTS MAY BE RETURNED IN ANY OF THE               FIR02380
C                        ABOVE CASES.                                               FIR02390
C                                                                                    FIR02400
C         EXAMPLE OF USAGE                                                           FIR02410
C                                                                                    FIR02420
C            THIS EXAMPLE MINIMIZES THE OBJECTIVE FUNCTION SHOWN IN THE             FIR02430
C            EXTERNAL FUNCTION FE(X).  THERE ARE TWO INDEPENDENT VAR-              FIR02440
C            IABLES X(1) & X(2), AND TWO IMPLICIT CONSTRAINT FUNCTIONS             FIR02450
C            X(3) & X(4) WHICH ARE EVALUATED AS AUXILIARY VARIABLES (SEE          FIR02460
C            EXTERNAL FUNCTION KE(X) ).                                            FIR02470
C                                                                                    FIR02480
C            DIMENSION  XS(4),XU(2),XL(2)                                            FIR02490
CC                                                                                   FIR02500
CC    STARTING GUESS                                                                 FIR02510
C         XS(1) = 1.0                                                                FIR02520
C         XS(2) = 0.5                                                                FIR02530
CC    UPPER LIMITS                                                                   FIR02540
C         XU(1) = 6.0                                                                FIR02550
C         XU(2) = 6.0                                                                FIR02560
CC    LOWER LIMITS                                                                   FIR02570
C         XL(1) = 0.0                                                                FIR02580
C         XL(2) = 0.0                                                                FIR02590
CC                                                                                   FIR02600
C         R = 9./13.                                                                 FIR02610
C         NTA = 5000                                                                 FIR02620
C         NPR = 50                                                                   FIR02630
C         NAV = 2                                                                    FIR02640
C         NV = 2                                                                     FIR02650
C         IP = 0                                                                     FIR02660
CC                                                                                   FIR02670
C         CALL BOXPLX (NV,NAV,NPR,NTA,R,XS,IP,XU,XL,YMN,IER)                        FIR02680
C         WRITE(6,1) ((XS(I),I=1,4),YMN,IER)                                        FIR02690
C   1 FORMAT (////,'   THE POINT IS LOCATED AT (XS(I)=) ',4(E13.7,5X),             FIR02700
C     1//,'   AND THE FUNCTION VALUE IS ',E13.7,'  IER = ',I5)                      FIR02710
CC                                                                                   FIR02720
C         STOP                                                                       FIR02730
C         END                                                                        FIR02740
CC                                                                                   FIR02750
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